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Sensitivity Analysis of the Gap Heat Transfer Model in BISON

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Abstract

This report summarizes the result of a NEAMS project focused on sensitivity analysis of the heat transfer model in the gap between the fuel rod and the cladding used in the BISON fuel performance code of Idaho National Laboratory. Using the gap heat transfer models in BISON, the sensitivity of the modeling parameters and the associated responses is investigated. The study results in a quantitative assessment of the role of various parameters in the analysis of gap heat transfer in nuclear fuel.

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CONTENTS

1. INTRODUCTION

This report summarizes the result of a NEAMS project focused on sensitivity analysis of the models governing the heat transfer, particularly in the gap between the fuel rod and the cladding in the BISON fuel performance code. BISON is an implicit, parallel, fully-coupled code under development at the Idaho National Laboratory (INL) [1]. BISON is built on the MOOSE computational framework [2] which allows for rapid development of codes involving the solution of partial differential equations using the finite element method. Nuclear fuel operates in an environment with complex multiphysics phenomena, occurring over distances ranging from inter-atomic spacing to meters, and times scales ranging from microseconds to years. This multiphysics behavior is often tightly coupled and many important aspects are inherently multidimensional.

BISON is able to simulate tightly coupled multiphysics and multiscale fuel behavior, for either 2D axisymmetric or 3D geometries. BISON code validation and assessment is presented in [3].

In BISON, there are several physical processes that may affect the thermal behavior of a fuel rod during normal operation. We desire to identify those models and parameters that most significantly affect the predicted centerline temperature during a typical problem. If we can narrow our focus to a small set of models and parameters, then performing a subsequent uncertainty analysis will present a much more tractable problem.

The Bison Theory Manual [4] provides a description of the models currently coded in BISON. Discussions were held with INL staff in order to identify those models that would be expected to potentially affect the fuel rod thermal response. These discussions identified several areas, including:

- Gap heat transfer modeling
- Fuel thermal properties
- Radial distribution of heat release
- Fission product induced swelling
- Fuel densification
- Effect of UO_2 cracking on gap width (denoted “relocation”)

This report focuses on primarily on the first item: the gap heat transfer model. Initially, we study it in isolation from the other models. The gap heat transfer is known to be a dominant contributor to overall heat transfer uncertainty and is by itself complicated.

In this report, we present three instances of the sensitivity analysis for the gap heat transfer model. The first study involves a small, standalone code that was written to study the analytic behavior of the gap heat transfer model used in BISON. The second study involves the sensitivity of the model parameters at the beginning of life. The third study involves the sensitivity of the model parameters in highly irradiated fuel.

The outline of this document is as follows: Section 1 describes the heat transfer model used in BISON. Section 2 outlines the sensitivity analysis method and software used. Section 3 provides results for the three cases (analytic model, beginning of life, and highly irradiated fuel). Section 4 presents the conclusions.

1.1. Bison Gap-region Heat Transfer Model

Gap heat transfer models in BISON are described in Section 13.1 of the Bison Theory Manual [4]. Figure 1 illustrates the region of interest.

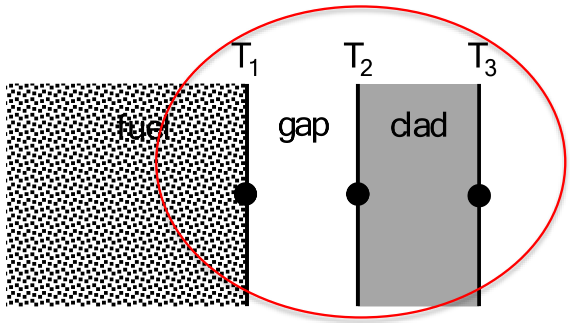

Figure 1. Gap region of interest for heat transfer

In Bison, the heat transfer rate across the gap (q, W/m^2) is modeled using the following simple relation,

$$q = h_{gap}(T_1 - T_2) \tag{1}$$

where the total effective heat transfer coefficient across the gap, h_{qap} (W/m^2 K, also called the gap conductance in Bison literature), is modeled as the sum of three distinct contributions: (1) conduction through the gas (h_q), radiation heat transfer (h_r), and the increase in heat transfer due to solid-solid contact (h_s).

$$h_{gap} = h_g + h_r + h_s \tag{2}$$

These individual contributions are modeled separately as follows

$$h_g(T) = \frac{k_g(T_g)}{d_g + C_r(r_1 + r_2) + (g_1 + g_2)} \tag{3}$$

$$h_s(P_c) = C_s \frac{2k_1k_2}{(k_1 + k_2)} \frac{P_c}{\delta^{1/2} H} \tag{4}$$

$$h_r(T) = \sigma \frac{(T_1^2 + T_2^2)(T_1 + T_2)}{\left(\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1 \right)} \tag{5}$$

where

d_g	gap thickness
$k_g(T)$	gas thermal conductivity (as function of temperature, species)
C_r	Empirical roughness coefficient
r_1+r_2	surface roughnesses of the two surfaces
g_1+g_2	temperature jump distance (see Eq. 13.3-13.6, Bison Theory Manual)
C_s	Empirical constant for solid-solid contact
k_1, k_2	thermal conductivity of materials on surface 1 and 2
P_c	contact pressure
δ	Avg. gas film thickness, approximated as $\delta = 0.8(r_1+r_2)$
H	Meyer harness of the softer material
σ	Stefan-Boltzmann constant = 5.669×10^{-8} W/(m^2 K^4)
ε_1, ε_2	emissivities of surface 1 and 2

Details of the Kennard model for the temperature jump distance (g_1+g_2) can be found in the Bison theory manual [4] section 13.1. Here we simply note that the Kennard model has a leading model coefficient that with nominal value 5756 which will be varied as part of the sensitivity study.

2. MAIN EFFECTS ANALYSIS

To perform the sensitivity analysis, we interfaced a toolkit called Dakota to the BISON fuel performance code on the High Performance Computing (HPC) machine called Fission at Idaho National Laboratory. Dakota allows a user to design computer experiments, run parameter studies, perform uncertainty quantification, and calibrate parameters governing their simulation model. A primary goal for Dakota is to provide scientists and engineers with a systematic and rapid means to obtain improved or optimal designs or understand sensitivity or uncertainty using simulation-based models. These capabilities generally lead to improved designs and better understanding of system performance [5].

One of the primary advantages that Dakota has to offer is access to a broad range of iterative capabilities through a single, relatively simple interface between Dakota and a simulator. In this context, we interfaced Dakota to BISON. To perform different types of analyses, it is only necessary to change a few commands in the Dakota input and start a new analysis. The need to learn a completely different style of command syntax and the need to construct a new interface each time you want to use a new algorithm are eliminated. For the work presented below, we were able to develop one interface between Dakota and BISON, and swap out a few lines in the Dakota input deck to run the various case studies.

There are many goals of running a computer experiment. One objective is to determine which inputs have the most influence on the output, or how changes in the inputs change the output. This is usually called *sensitivity analysis*. We have focused on sensitivity analysis in these studies, in contrast to uncertainty quantification, which aims at obtaining a probability distribution on the outputs given probability distributions on the inputs. In this work, no probability distributions are assumed.

In order to identify the input parameters that have the most significant influence on the output, a sensitivity analysis technique called main effects analysis is used. This technique assesses the effect of an independent variable (input parameter) on a dependent variable (output quantity), averaging across the levels of the other independent variables. Orthogonal array sampling (OAS) is used to perform the main effects study [5,6]. With orthogonal arrays, the input parameters are specified at fixed levels (e.g. low, medium, high), and the OAS design is constructed so that the sample columns (e.g. columns for particular parameter settings) are orthogonal to each other. We used a full factorial orthogonal array for these studies, which means we considered the full tensor product of all the combinations of parameter levels.

Orthogonal arrays allow one to perform main effects analysis. This is a sensitivity analysis method which identifies the input variables that have the most influence on the output. In main effects, the idea is to look at the mean of the response function when variable A (for example) is at level 1 vs. when variable A is at level 2 or level 3. If these mean responses of the output are statistically significantly different at different levels of variable A, this is an indication that variable A has a significant effect on the response. The orthogonality of the columns is critical in performing main effects analysis, since the column orthogonality means that the effects of the other variables 'cancel out' when looking at the overall effect from one variable at its different levels.

3. SENSITIVITY ANALYSIS RESULTS

This section provides results for the three case studies of the gap heat transfer model: an analytic model, beginning of life, and highly irradiated fuel.

3.1 Analytic Model

To study the equations outlined in Section 1.1, a small Fortran code (here called GapCladHT) was written to act as a fast-running surrogate for the entire BISON code, focusing only on the isolated region illustrated in Figure 1. The equations used in this simple model are as follows.

$$T_1 = T_3 + q\left[\frac{1}{h_{gap}} + \frac{d_c}{k_c}\right], \tag{6}$$

$$T_2 = T_3 + q\left[\frac{d_c}{k_c}\right] \tag{7}$$

where

T_1	= Temperature of the fuel surface
T_2, T_3	= Temperature of the inside and outside of the clad, respectively
q	= heat flux through the surfaces (W/m^2)
d_c	= clad thickness (m)
k_c(T)	= clad thermal conductivity (as function of temperature)

Inserting the models used in BISON for the three contributions to the total heat transfer coefficient (see equations (3)-(5) above) we can write

$$T_1 = T_3 + q\left[\frac{1}{\left(h_g(T) + h_s(P_c) + h_r(T)\right)} + \frac{d_c}{k_c(T)}\right] \tag{8}$$

The models and correlations used were taken directly from the equations modeled in BISON. A code listing is provided in Appendix A.

Each of the following problem conditions must be specified for a particular analysis.

T_3	clad outer-surface temperature
q,	heat flux
d_c	clad thickness
d_g	gap thickness
P_c	contact pressure

Table 1 lists, models and parameters that were not varied during the sensitivity analysis.

Table 2 lists the six parameters whose effects were included in the sensitivity study using Dakota. The quantities kg_mult, kc_mult and ken_mult are multiplier coefficients of the computed values for the gas thermal conductivity, clad thermal conductivity and temperature jump distance (Kennard model) respectively.

Table 1. Specified models and parameters not varied

Quantity	Model or Value	Comments
T_3	513 K	used by Bison for ifa_431_rod1 [3]
q	6.5e5 W/m^2	See Table 3
d_c	9.5e-4 m	See Table 4
P_c	0.	Sets $h_s = 0$
$k_c(T)$	$7.511 + .02088*T - 1.45e\text{-}5*T^2 + 7.688e\text{-}9*T^3$	Ref. [8]
$k_g(T)$	$0.0468 + 3.81e\text{-}4*T - 6.79e\text{-}8*T^2$	Ref. [9]
r_1+r_2	2.8e-6 *(2.16e-6 + 6.35e-7= 2.795e-6 m)*	used by Bison for ifa_431_rod1 [3]
g_1+g_2	Kennard model with P_{pin}=1.2e5 N/m^2	used by Bison for ifa_431_rod1 [3]

Table 2. Parameters varied in the sensitivity study

Parameter	low	nominal	high
d_g	**1.e-6**	**1.e-5**	**1.e-4**
C_r	1.0	3.2*	10.
ε_1, ($\varepsilon_2 = 1.0$)	0.0	0.5	1.0
kg_mult	0.9	1.0	1.1
kc_mult	0.9	1.0	1.1
ken_mult	0.75	1.0	1.25

** value used by Bison for ifa_431-rod1 test [3]*

Note that there is some uncertainty about parameter values to use for the size of the gap and the fuel thermal conductivity. The geometric parameters we chose to use for this study relative to other references are described in Figure 2 and Tables 3 and 4.

Table 3 Comparison of fuel rod dimensions

	Fuel pellot radius (m)	Clad inner radius (m)	Clad outer radius (m)	Gap thickness (m)	Clad thickness (m)	Total gapclad (m)
Table 5.1 in [10]	4.70e-3	4.75e-3	5.36e-3	5.0e-4	6.1e-4	11.1e-4
ifa_431_rod1	5.34e-3	5.45e-3	6.40e-3 m	1.1e-4	9.5e-4	10.6e-4
Remirez et al. [11]	4.30e-3	4.33e-3	4.83e-3	0.3e-4	5.0e-4	5.3e-4
gapcladHT	**-**	**-**	**-**	**10^{-6} -> 10^{-4}**	**9.5e-4**	**-**

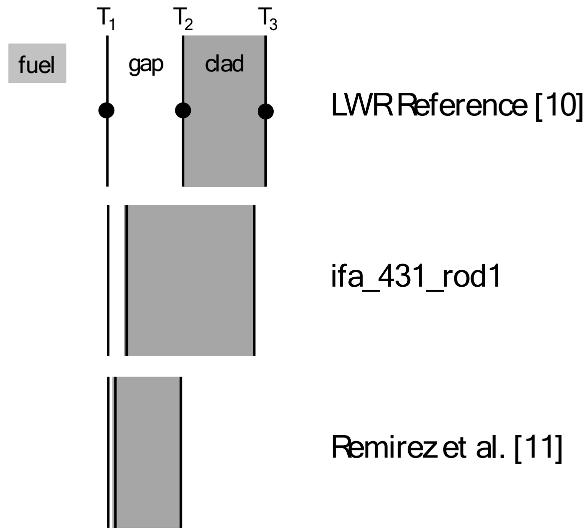

Figure 2. Illustration of fuel rod dimensions compared in Table 3

Table 4 Comparison of fuel rod thermal conditions

	Fuel Heat flux (W/m^2)	Clad outer Temperature (K)
Table 5.1 in [10]	~6.4e5	~620
ifa_431_rod1	variable	513
Remirez et al. [11]	4.3e5	750
gapcladHT	**6.5e5**	**513**

Analytic Model Results

Several plots are presented below to visually quantify the results from doing a main effects parameter study using Dakota and GapCladHT.

Figure 3 plots results of varying the six parameters listed in Table 2 and shows that over the ranges specified, changes in gap width have by far the largest effect on fuel surface temperature. However, changes to the roughness coefficient and gas thermal conductivity were also significant.

To better understand the relative importance of the other five parameters, a set of three additional main effects studies were performed, one for each of the three gap widths considered. These results are shown in Figures 4, 5 and 6.

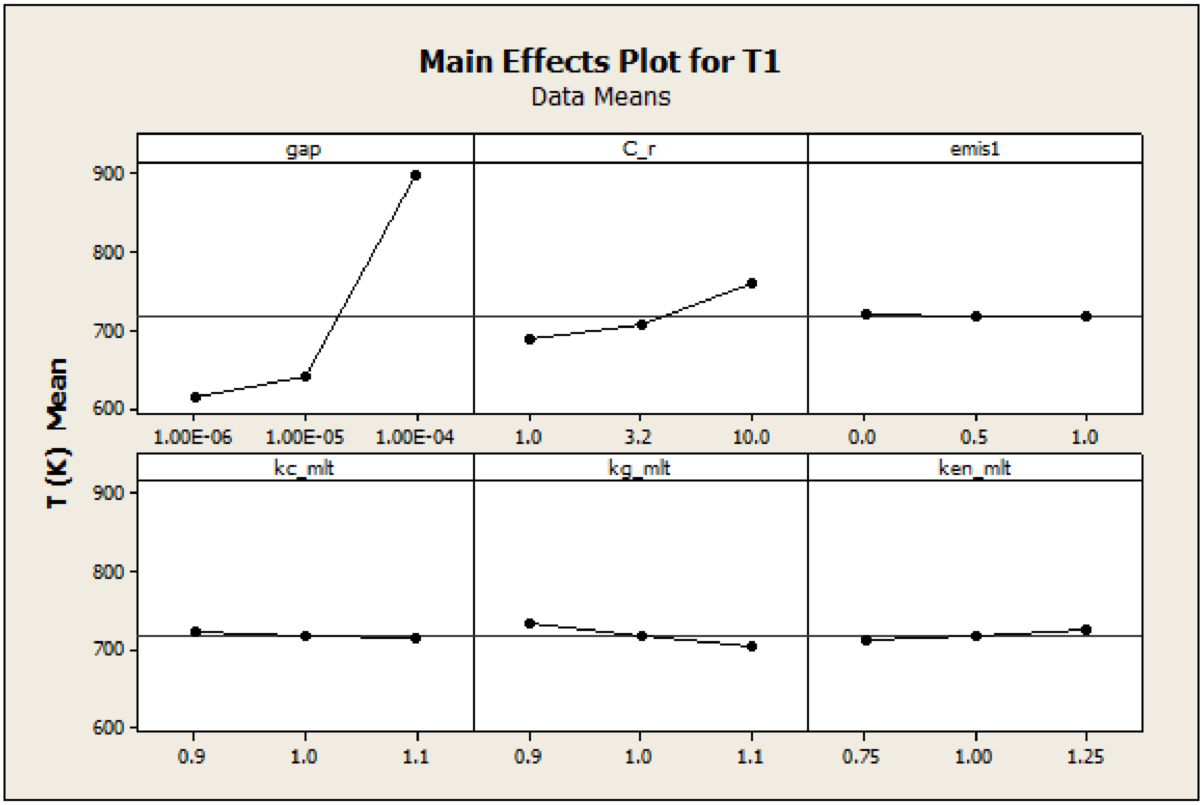

Figure 3. Six-parameter main effect plots for simple GapCladHT model

The magnitude of the variations used in this study were chosen by subjective judgment of the authors as representing the current range of uncertainty for these values.

By comparing the plots in Figure 4 – 6 we can observe the following.

- Varying the roughness coefficient over the specified range was the most significant factor among the five parameters for all gap widths.
- Varying the emissivity over its entire range of possibility has only a very small impact, demonstrating that radiation heat transfer is relatively weak under these conditions. Only in Figure 6 (large gap width), where the surface temperatures are several hundred degrees higher do we begin to see some noticeable impact.
- Figure 6 shows that the gas thermal conductivity can be important as the gap width becomes large. This directly reflects that the thermal resistance due to thermal conduction across the gap scales linearly with the gap width.

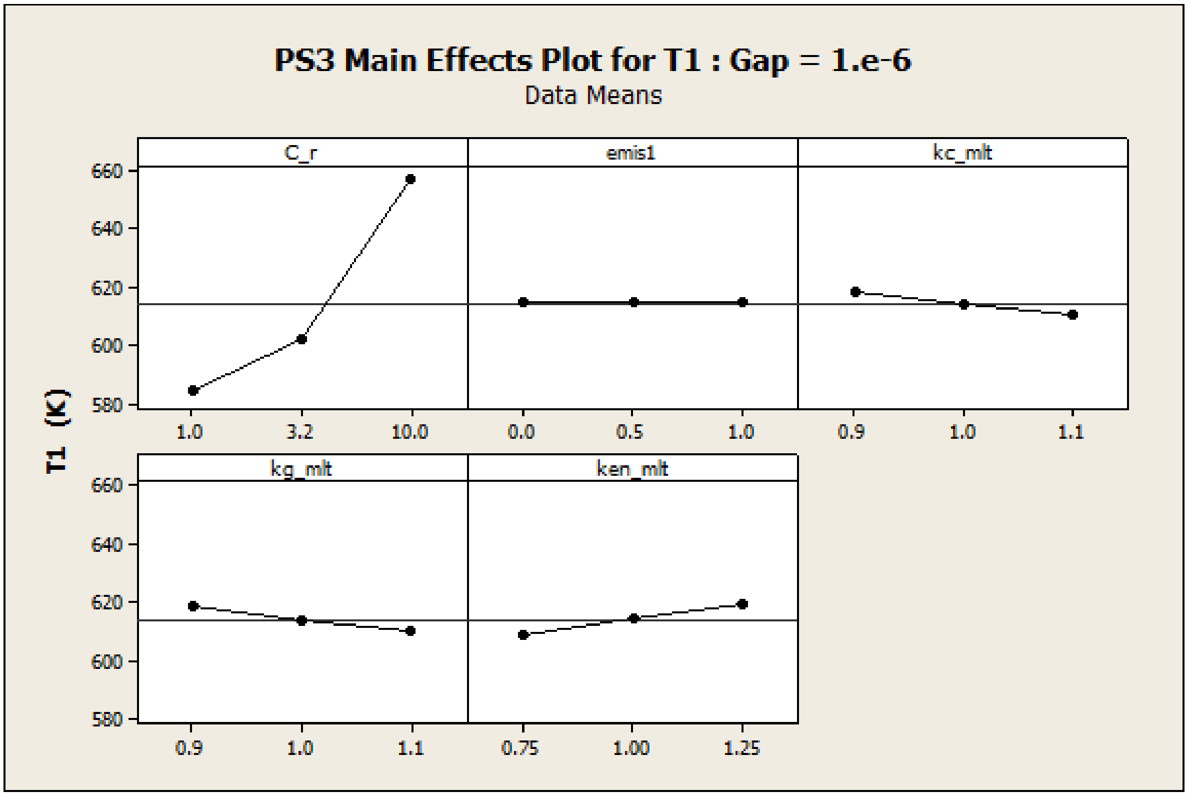

Figure 4. Five-parameter main effect plots for simple GapCladHT model: gap=10^{-6} m.

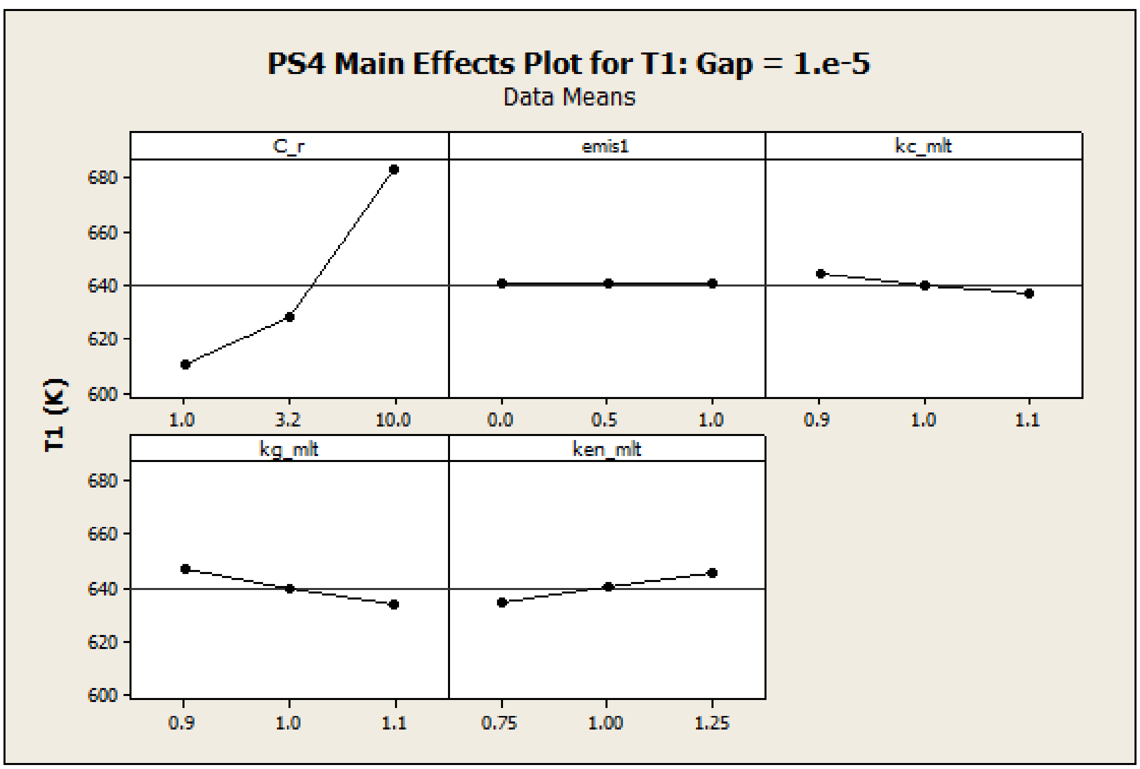

Figure 5. Five-parameter main effect plots for simple GapCladHT model: gap=10^{-5} m.

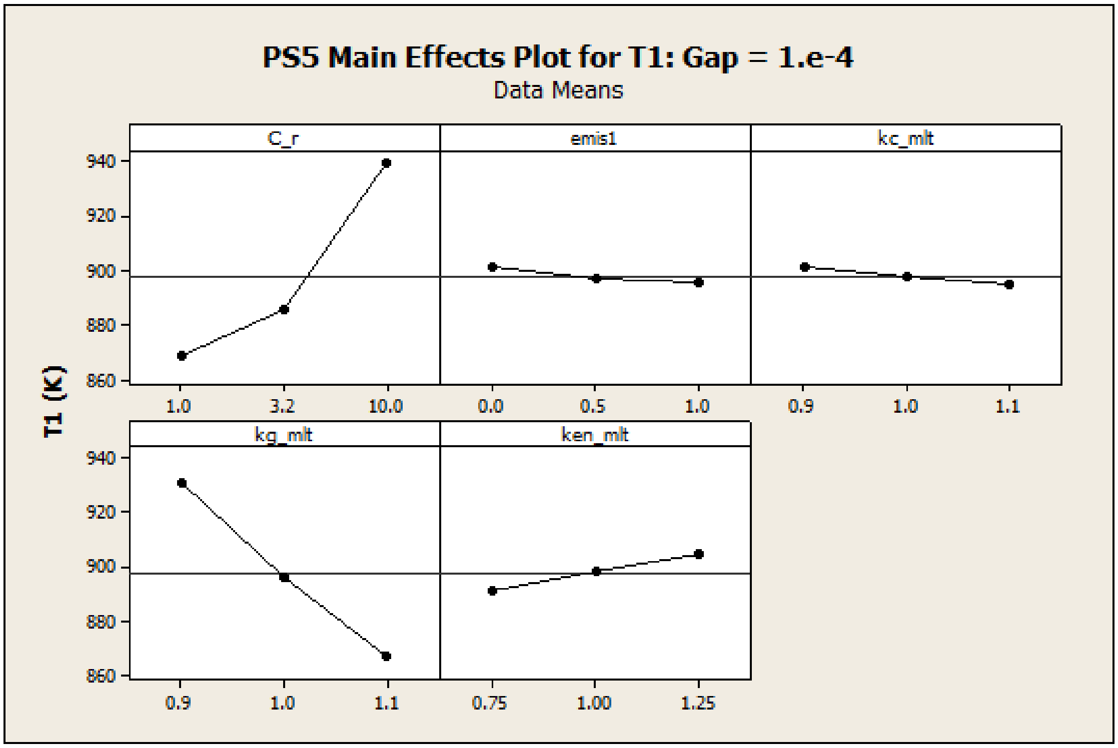

Figure 6. Five-parameter main effect plots for simple GapCladHT model: gap=10^{-4} m.

3.2 Beginning of Life Analysis

To study the effect of the gap heat transfer at the beginning of a fuel rod's life, we performed a sensitivity study of the Bison code analysis of the Halden IFA_431-rod test as described in [3]. The experiments referred to as IFA-431 and IFA-432 were heavily instrumented assemblies irradiated in the Halden Boiling Water Reactor in Norway. The tests provided a large amount of well-characterized data under realistic LWR conditions, and have been used extensively for assessing and improving fuel rod performance calculations [12]. Measurements included fuel centerline temperature histories from thermocouples located in the top and bottom end of the fuel column. All test rods contained fresh high density (95% TD) sintered UO_2 in Zircaloy 2 cladding. The reactor was operated at typical BWR conditions. Details concerning rod geometry and materials, power history and axial power profile, and reactor operating conditions, are given in references [13] and [14]. Although measurements were taken through an extended fuel life, the focus here is on beginning of fuel life, before more complex behavior associated with irradiation and high burnup occurs.

Table 5 lists the three parameters whose effects were included in the BISON sensitivity study using Dakota. Two of these, the roughness coefficient Cr and the Kennard coefficient were previously included in the sensitivity study described above using the gapcladHT model. In addition, a multiplier on the fuel thermal conductivity was also varied by +/- 25%. Of note is that the gap width is not specified but is part of the solution, and varies throughout the simulation. Its value is affected directly and/or indirectly by many of the models in BISON, and thus cannot be directly studied in this context.

For this sensitivity study we concern ourselves with BISON-predicted temperatures that are nearest to the locations of two test thermocouples, here denoted "T_up_tc" (for the upper thermocouple) and "T_low_tc" (for the lower thermocouple). However, we do not compare the results of the simulation to test data, but rather look at the sensitivity of the predictions at the end of the test to changing the three parameters listed in Table 5. As before, the ranges used for this study were chosen by the subjective judgment of the authors.

Figure 7 shows main effects results for the sensitivity study when comparing to the upper thermocouple. Figure 8 is for the lower thermocouple. Qualitatively, both show almost identical results. The parameter variation with the greatest effect is the thermal conductivity of the fuel, followed by the roughness coefficient, and lastly the Kennard model coefficient. Here a point should be made concerning the results for the roughness coefficient and the coefficient for the Kennard model of the temperature jump. Note that in equation (3), both of these terms take the same form, and thus the sensitivity to both of these must be the same for the same relative change. But in the sensitivity study done here, the roughness coefficient was varied in both directions by a factor of 3X, whereas the Kennard model coefficient was only varied by a factor of (5/4)X. As mentioned, this choice reflected the subjective judgment of the authors,

Using Paraview to visualize the results of the simulation showed that during the run, the gap width shrunk quickly by about 40% and then fluctuated around that value, reflecting the power fluctuations that occurred during the test. However, the gap was never smaller than ~30% of its initial value of (1.1e-4 m) and its ending value was about 40% (i.e. ~0.5e-4 m).

Table 5 Bison input parameters varied in the sensitivity study for Halden IFA 431 Beginning of Life case

Parameter	low	nominal	high
C_r	1.0	3.2	10.
Kennard Coefficient	4317	5756	7195
kf_mult	0.75	1.0	1.25

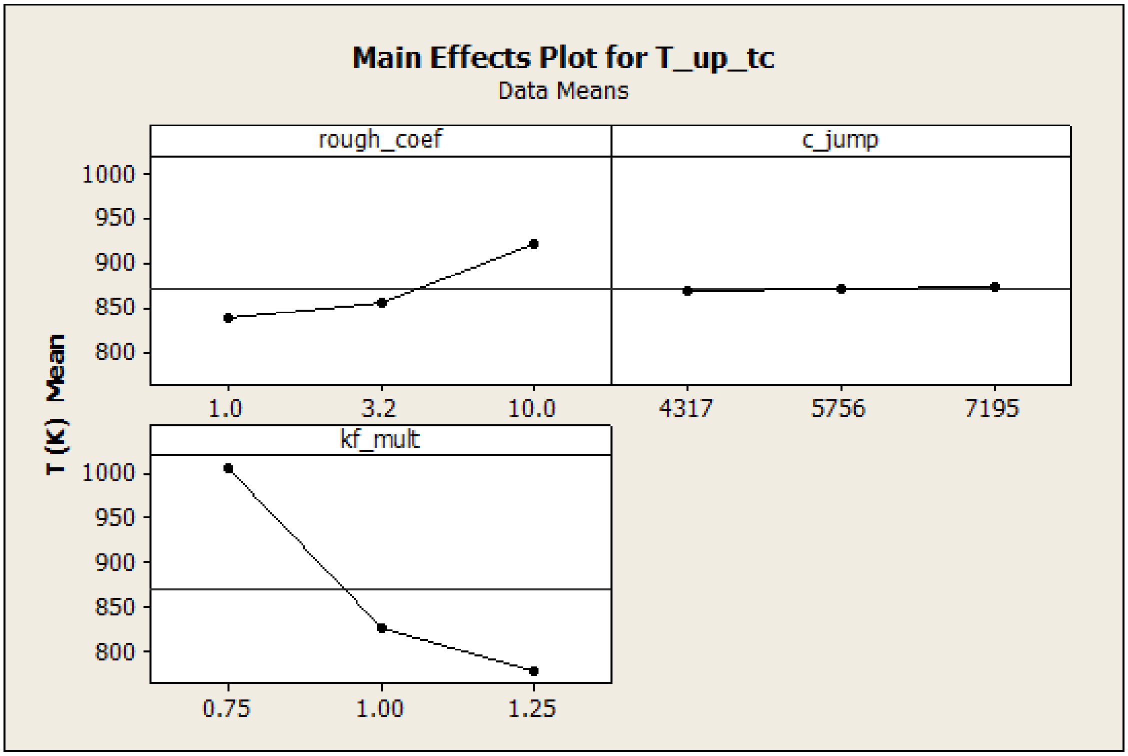

Figure 7. Three-parameter main effects plots for Bison predictions of T_up_tc

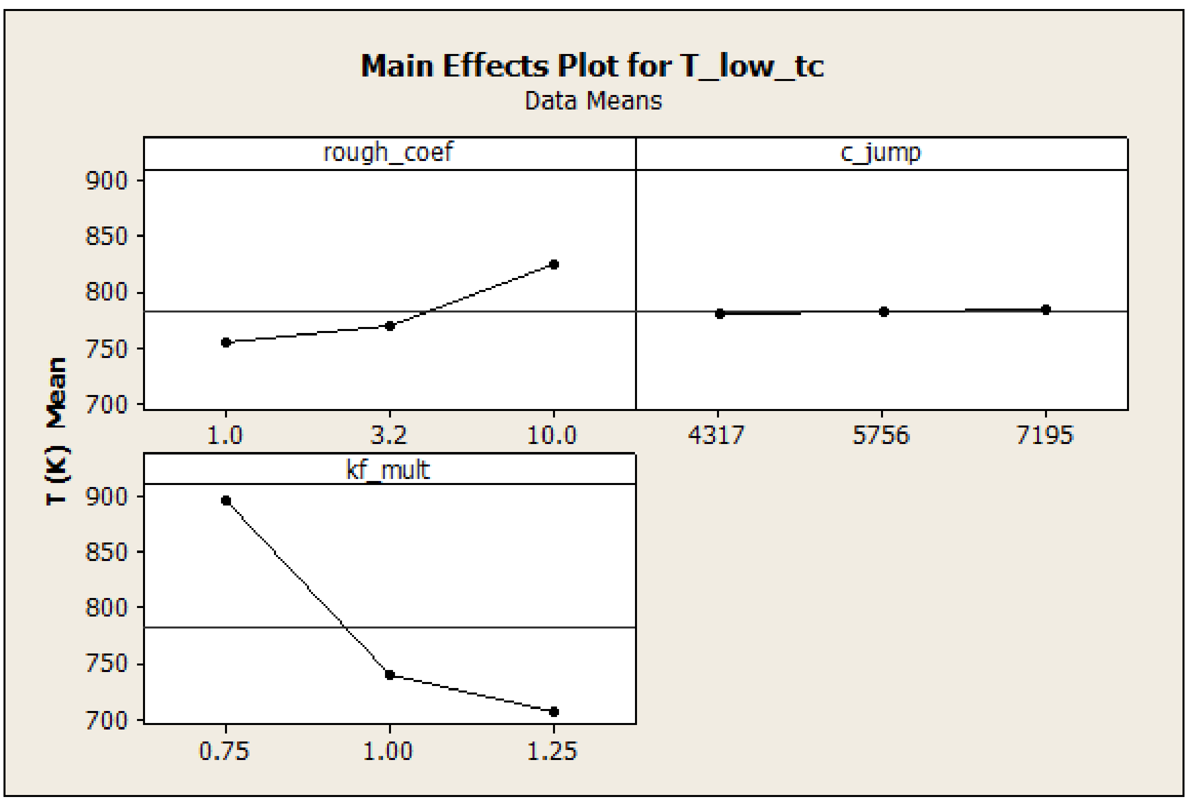

Figure 8. Three-parameter main effects plots for Bison predictions of T_low_tc

Two additional Bison-related sensitivity issues were also looked at. The first of these concerns the question of mesh refinement and mesh convergence. The radial resolution used for all of these cases was 12 radial elements in the fuel and 4 in the clad. A 2X more refined mesh was created that had 24 radial elements in the fuel, and the Bison calculation was repeated under the nominal conditions. It was found that the end-of-run temperatures changed less the 0.2 degrees (specifically, T_up_tc 813.932 -> 813.736 K). This suggests that the mesh resolution was sufficient for the purposes of this study.

The second question concerns the model for how the power was radially distributed within the fuel. The default Bison model tends to yield a peaking of the power closer to the outer surface of the fuel pin instead of at its centerline. To get a preliminary sense of how important this model may be to the predicted centerline temperature, an additional run was made with this power distribution model turned off (which yields a uniform power distribution). It was found that the end-of-run temperatures at the centerline locations of interest changed about 15 degrees (specifically, T_up_tc 813.932 -> 828.320 K).

Note that the results presented in Figures 7 and 8 were based on the actual power profile from Halden IFA-431 Rod 1, which had a very noisy power profile as shown in Figure 9. We were interested in seeing if we would obtain a similar sensitivity analysis with a much simpler, "smoothed" power profile which has approximately the same total power over the timeframe. This would allow us to perform studies over longer times with simpler power profiles which require less run-time in BISON. We created a simpler power profile as shown in Figure 9.

We performed the same sensitivity analysis with the smoothed power profile shown in blue in Figure 9. The results are shown in Figures 10. Note that Figure 10 is nearly identical to Figure 7 which was calculated with the actual power profile shown in red in Figure 9. The similarity of these plots leads us to conclude that using a smooth power profile for the purposes of sensitivity analysis of these parameters on centerline fuel temperature is sufficient.

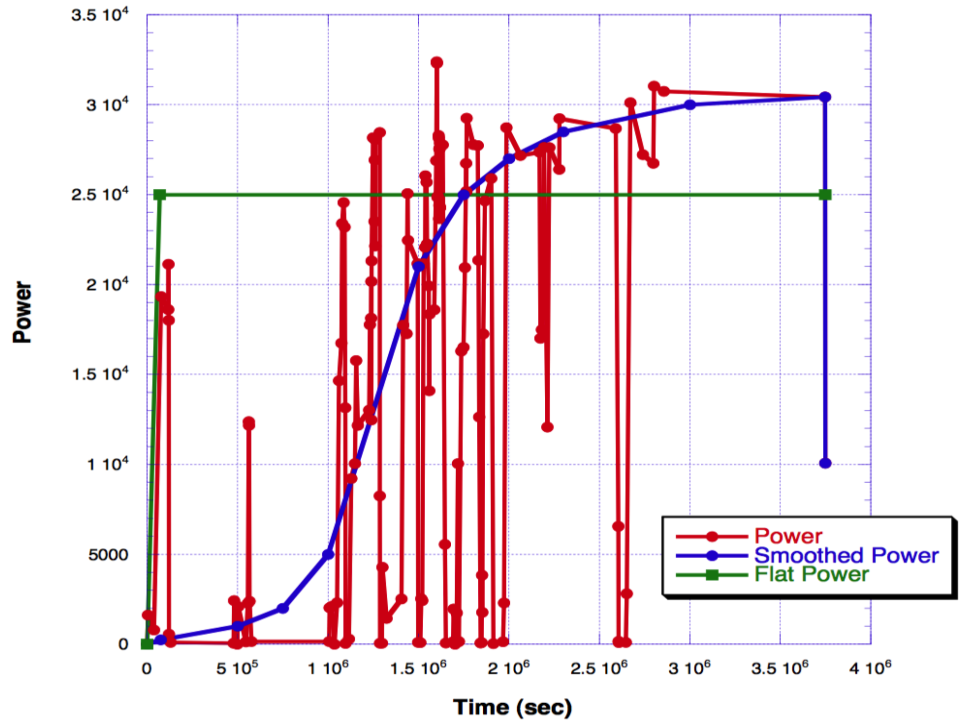

Figure 9. Halden IFA-431 Rod 1 Power profile (red), equivalent flat power (green), and smoothed power profile used in subsequent studies (blue).

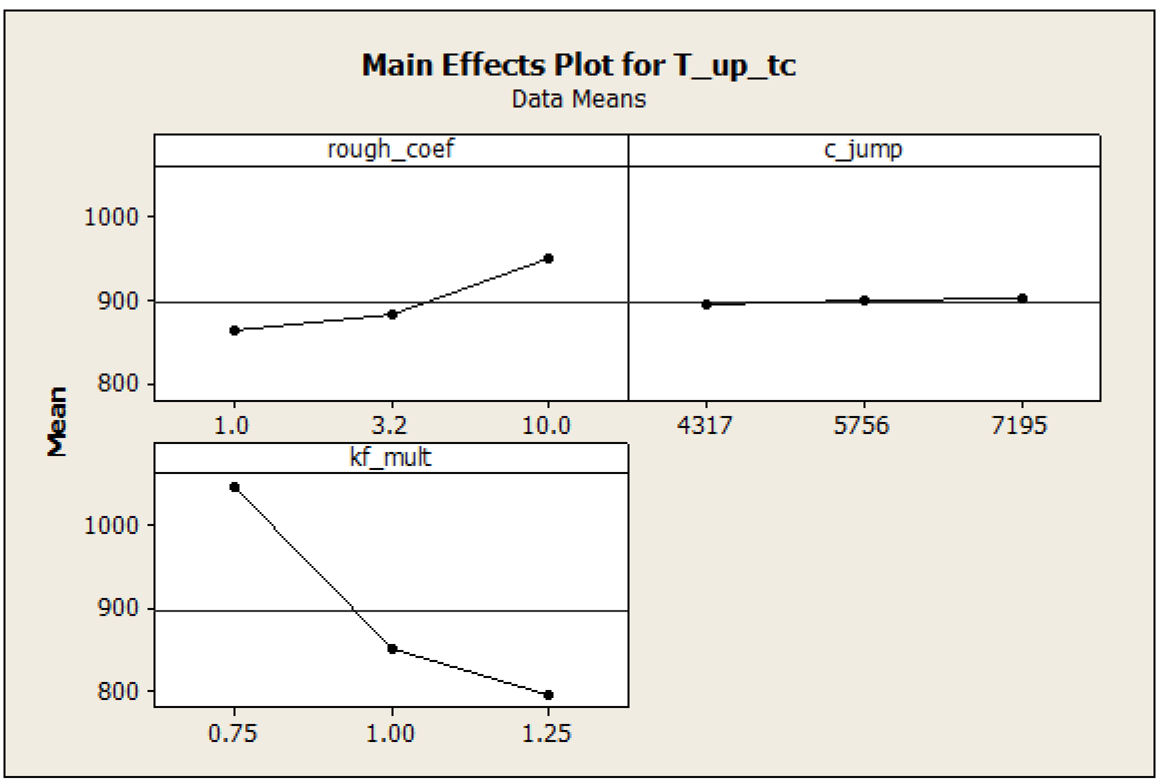

Figure 10. Three-parameter main effects plots for Bison predictions of T_up_tc based on smoothed power profile.

Finally, we performed one additional study in which we modified the range on the multiplier for the roughness coefficient (now 1, 2, and 4) and we added a multiplier on the gas thermal conductivity, with values (0.9, 1.0, and 1.1). The main effects plot for this analysis is shown in Figure 11.

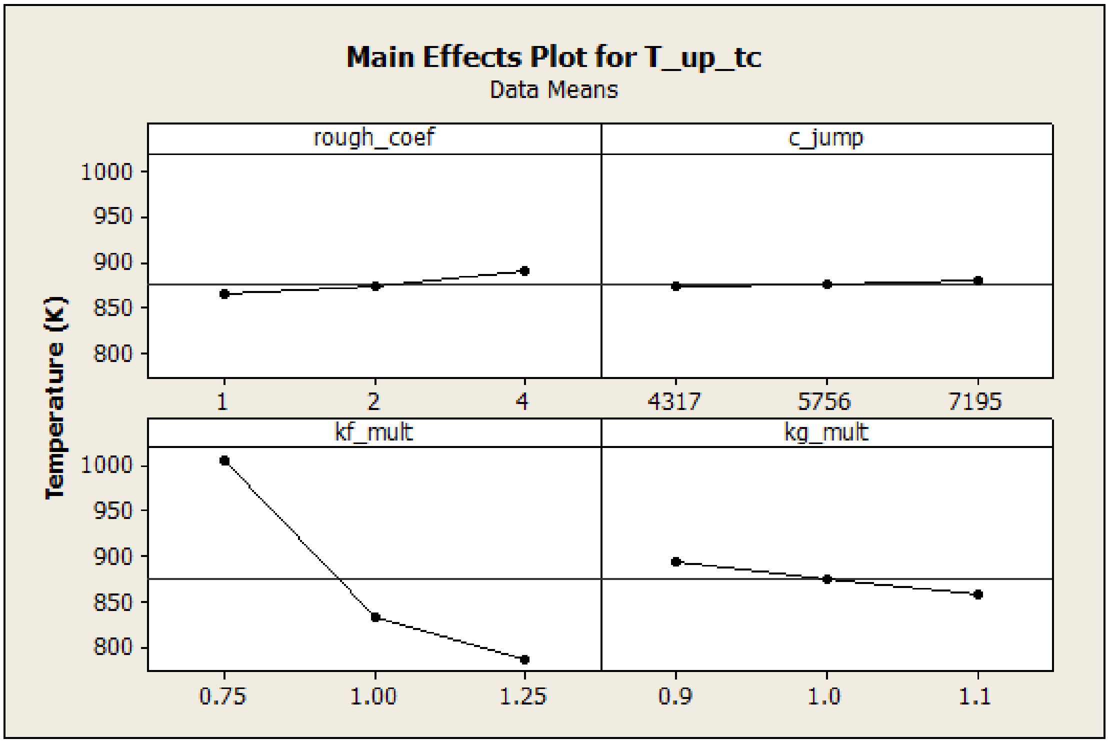

Figure 11. Four-parameter main effects plots for Bison predictions of T_up_tc based on smoothed power profile.

Based on all of these sensitivity analyses, we ranked the relative importance of each of the parameters and models considered in the numerical studies presented above. Table 6 summarizes this by listing the sensitivity to changing the different parameters and models over a certain range in terms of an associated temperature change ΔT. They are ordered with the largest sensitivities listed first. Note that these results depend on the variations chosen for parameters. Different ranges on the parameters will result in different sensitivities.

Table 6. Summary Results for GapCladHT or Bison parameters varied in the sensitivity study

Parameter or Model	Variation Range	ΔT (K) change
gap thickness – In Bison this is a function of all physics/models affecting fuel density/swelling. Hard to separate.	$10^{-6} < 10^{-4}$ m	~300
k_f thermal conductivity of the fuel	+/- 25%	~250
C_r roughness coefficient	10X	~70
k_g thermal conductivity of the gas in the gap	+- 10%	~30-50
rpf_active switch (on/off) controlling radial energy deposition	on/off	~15
k_c_thermal conductivity of the clad	+/- 10%	~10
Temperature jump model (Kennard model)	+/- 25%	~5-10
Surface emissivity – (radiation heat transfer)	$0 < \varepsilon < 1$	< ~3

3.3 Irradiated Fuel

To study the effect of the gap heat transfer in higher burn up situations we performed a sensitivity study of a Bison code analysis of the Risø AN3 test as described in [3]. The Risø AN3 experiment was one of the FUMEX-II priority cases [15] and was conducted at the Risø DR3 water-cooled HP1 rig. This experiment utilized a re-fabricated fuel rod from a pressurized water reactor fuel pin (CB8) irradiated in the Biblis A PWR over a duration of four reactor cycles. The re-fabricated rod (CB8-2R) was shortened and fitted with a fuel centerline thermocouple and pressure transducer [16] for use in the experiment.

As shown in Figure 12, the power history consists of two parts. The base irradiation period extends for just over three years (1198.25 days), corresponding to the time when the fuel rod was in the Biblis A PWR. The second, much shorter Risø AN3 experimental irradiation period was for only about 3 days, and is shown in greater detail in Figure 13.

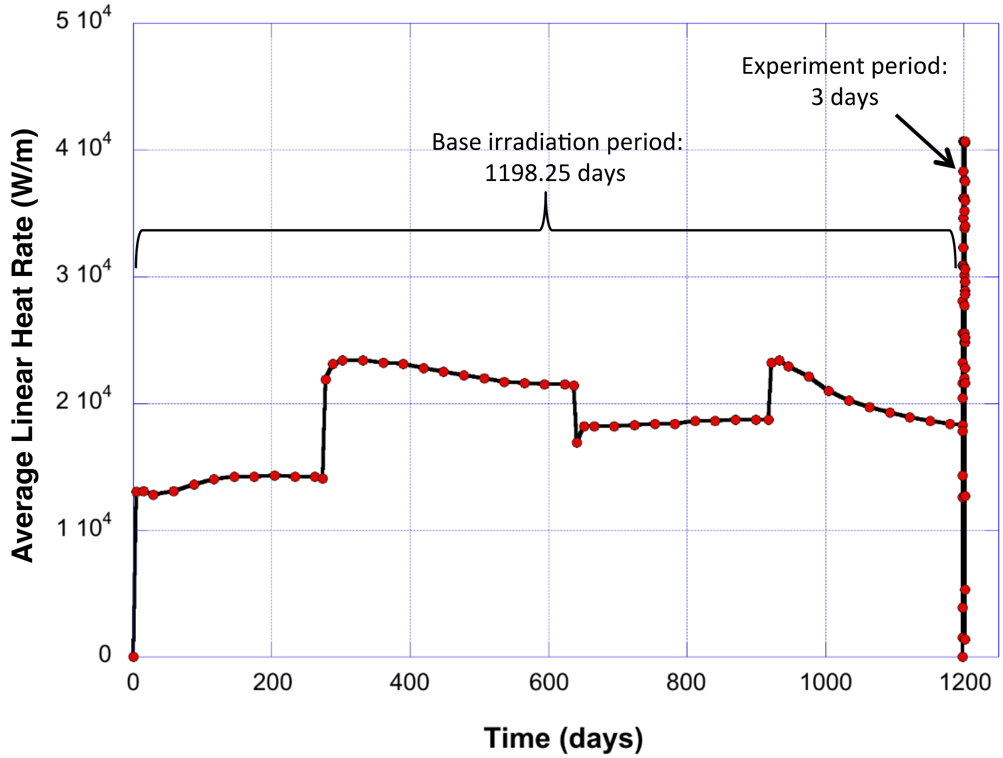

Figure 12 Riso3 Power history, including the base irradiation period (~1200 days) and the experimental irradiation period (~3 days).

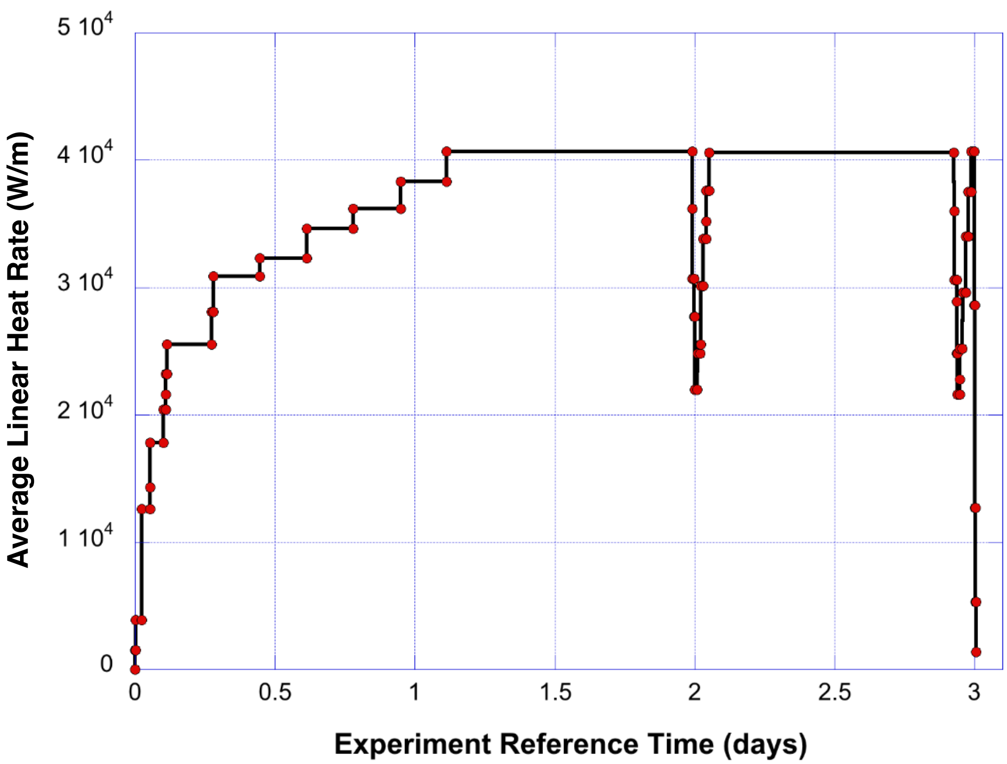

Figure 13 Riso3 Power history for the experimental irradiation period.

Table 7 lists the six parameters whose effects were included in the sensitivity study using Dakota. The quantities kf_mult, kg_mult are multiplier coefficients on the normal computed values for the fuel and gas thermal conductivity.

Table 7 Bison input parameters varied in the sensitivity study for Riso3

Parameter	low	nominal	high
Roughness coefficient, C_r	1.0	2.0	4.0
Kennard temperature jump model coefficient, C_jump	4317	5756	7195
Multiplier on fuel thermal conductivity, kf_mult	0.75	1.0	1.25
Multiplier on gap gas thermal conductivity, kg_mult	0.9	1.0	1.1
Contact model coefficient, C_contact	5	10	20

Dakota was used to perform a main effects sensitivity study of the Bison code predictions where the output metrics of interest were the mid-plane centerline temperature of the fuel and the corresponding mid-plane gap conductance. This study required that a total of 243 separate runs be made. Each run was assigned eight processors on the INL fission1 computer. Run times varied from 4-12 hours, depending on the conditions.

Data was extracted at two points in time: (1) at the very end of the base irradiation period, but just before the power ramp-down (time=103528800 sec.), and (2) at the end of the experimental irradiation period just before power ramp-down (time=103788200 sec.).

3.4 Sensitivity Analysis: Base Irradiation Period

This section outlines the sensitivity of the parameters to the results at the end of the base irradiation period, at 103528800 seconds, before the power ramp-down. Figure 14 shows the main effects of the parameters on the mid-plane centerline temperature, and Figure 15 shows the main effects of the parameters on the mid-plane gap conductance. Note that the thermal conductivity of the fuel is the dominant parameter for the centerline temperature, while the roughness coefficient is the dominant parameter for the gap conductance.

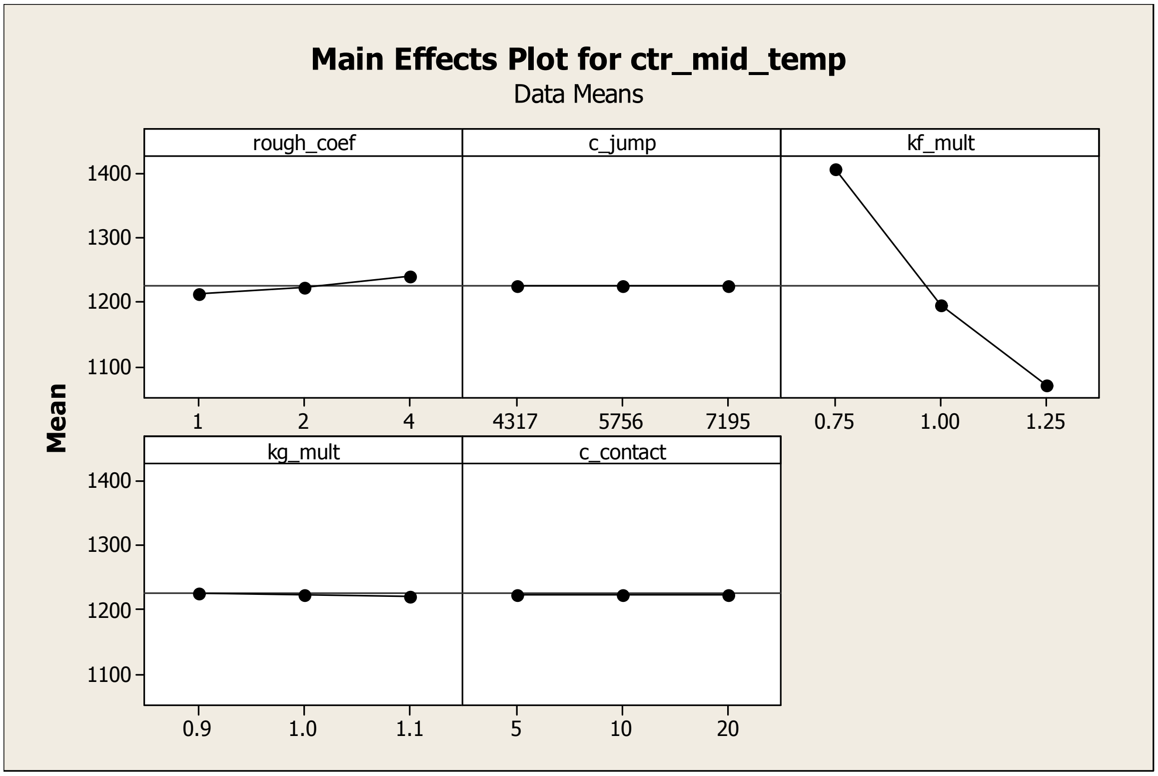

Figure 14. Base irradiation case: Main effects for mid-plane centerline temperature (K).

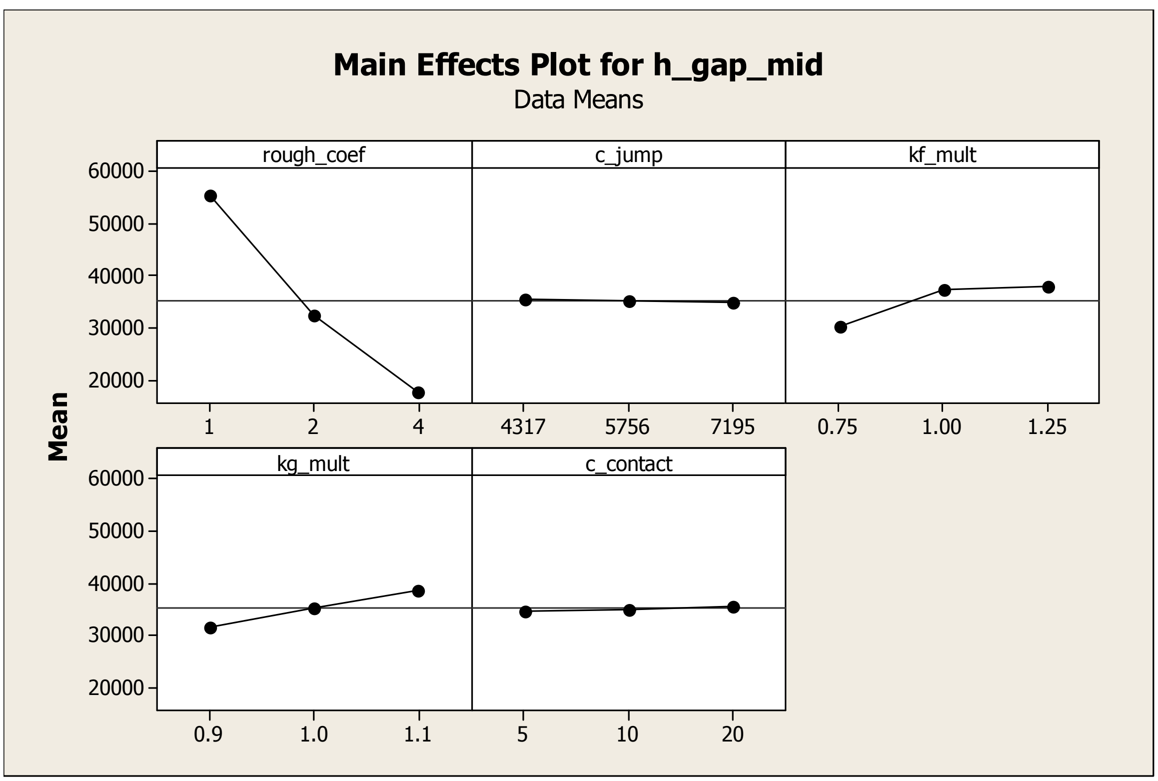

Figure 15. Base irradiation case: Main effects for mid-plane gap conductance (W/m^2 K).

Tables 8 and 9 show the correlation matrices for the centerline temperature and the gap conductance. The most significant correlations are highlighted in yellow. Correlations vary between -1 and 1, with -1 meaning strongly negatively correlated (as one variable increases, the other decreases) and 1 meaning strongly positively correlated. Note the correlations between the parameters are zero, which is what we should see because the main effects studies were performed with orthogonal arrays which means there are no correlations amongst the inputs (e.g. the parameter sample columns are orthogonal to each other). The thermal conductivity multiplier is strongly negatively correlated with the centerline temperature and mildly positively correlated with the gap conductance. The roughness coefficient is negatively correlated with gap conductance.

Table 8: Correlation matrix for ctr_mid_temp

	rough_coef	c_jump	kf_mult	kg_mult	c_contact
c_jump	0				
kf_mult	0	0			
kg_mult	0	0	0		
c_contact	0	0	0	0	
ctr_mid_temp	0.085	0.001	-0.985	-0.015	-0.003

Table 9: Correlation matrix for h_gap_mid_

	rough_coef	c_jump	kf_mult	kg_mult	c_contact
c_jump	0				
kf_mult	0	0			
kg_mult	0	0	0		
c_contact	0	0	0	0	
h_gap_mid	-0.905	-0.013	0.199	0.173	0.022

Figures 16-20 show boxplots of the data, across the various levels of the parameters. This provides more detail than the main effects plots. There is more detail about the sensitivity analysis, especially the Analysis of Variance (ANOVA) results, in Appendix B.

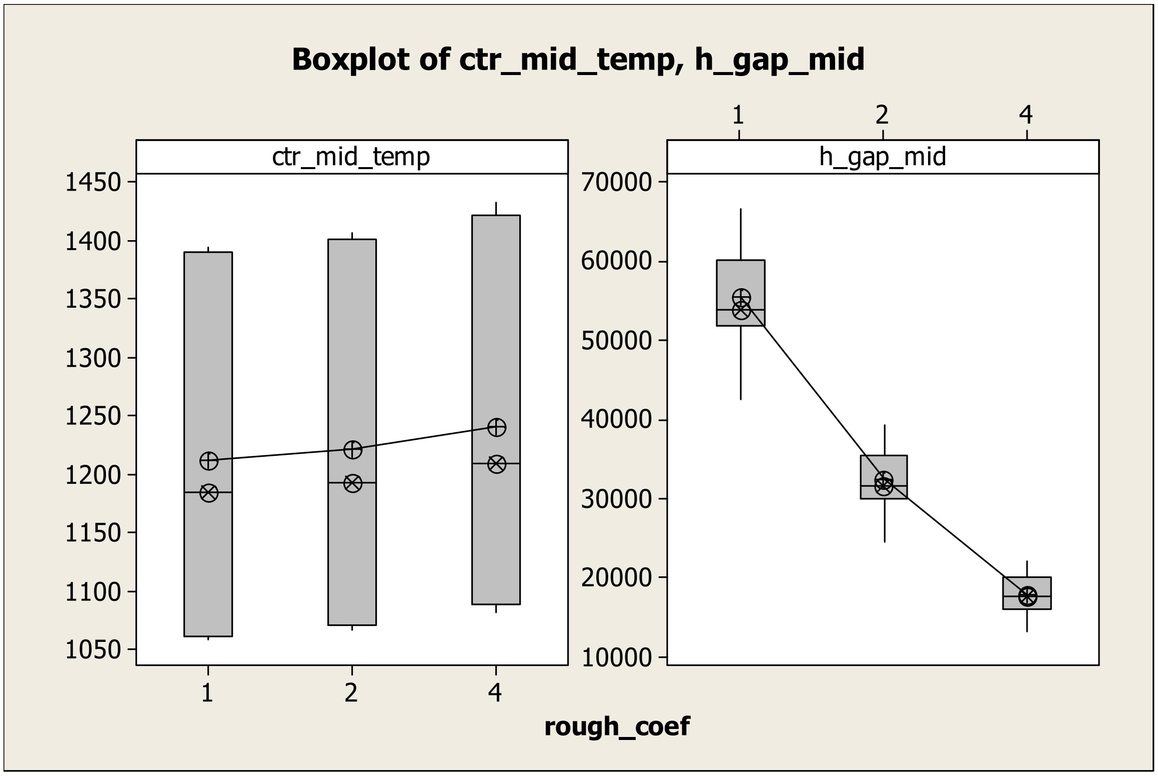

Figure 16: Boxplots based on roughness coefficient.

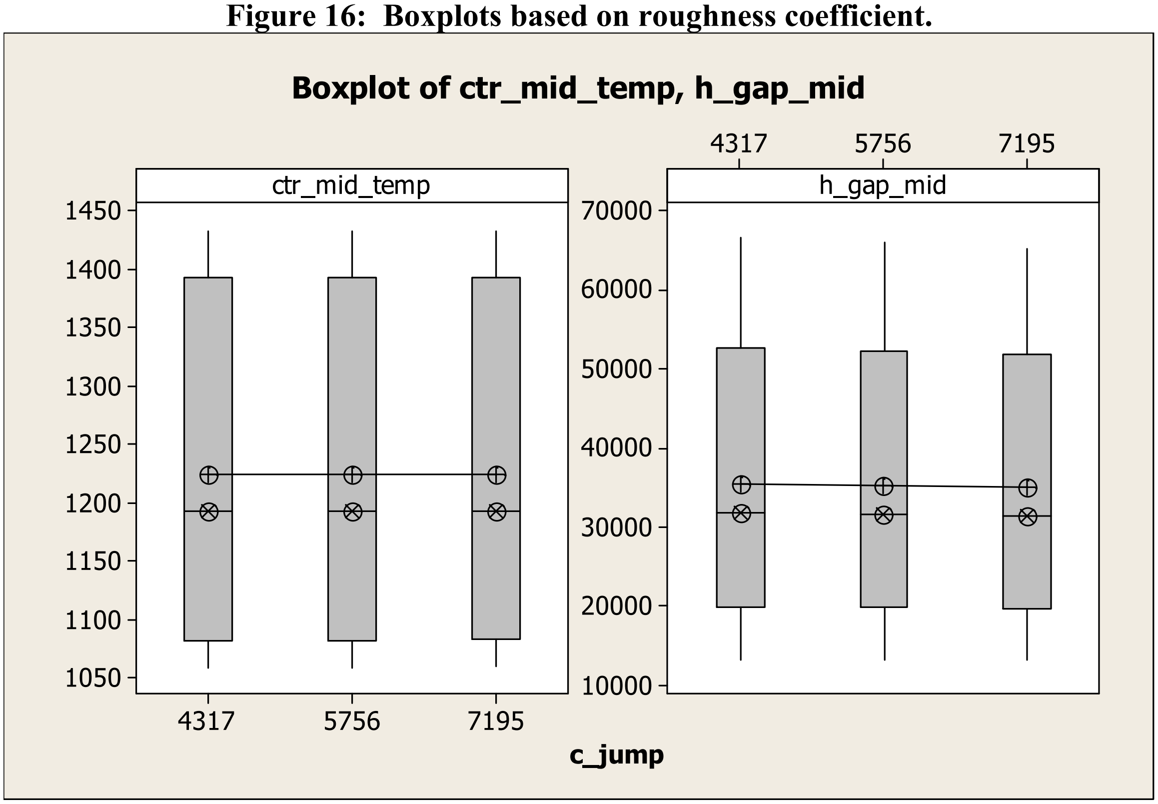

Figure 17: Boxplots based on Kennard temperature jump model coefficient.

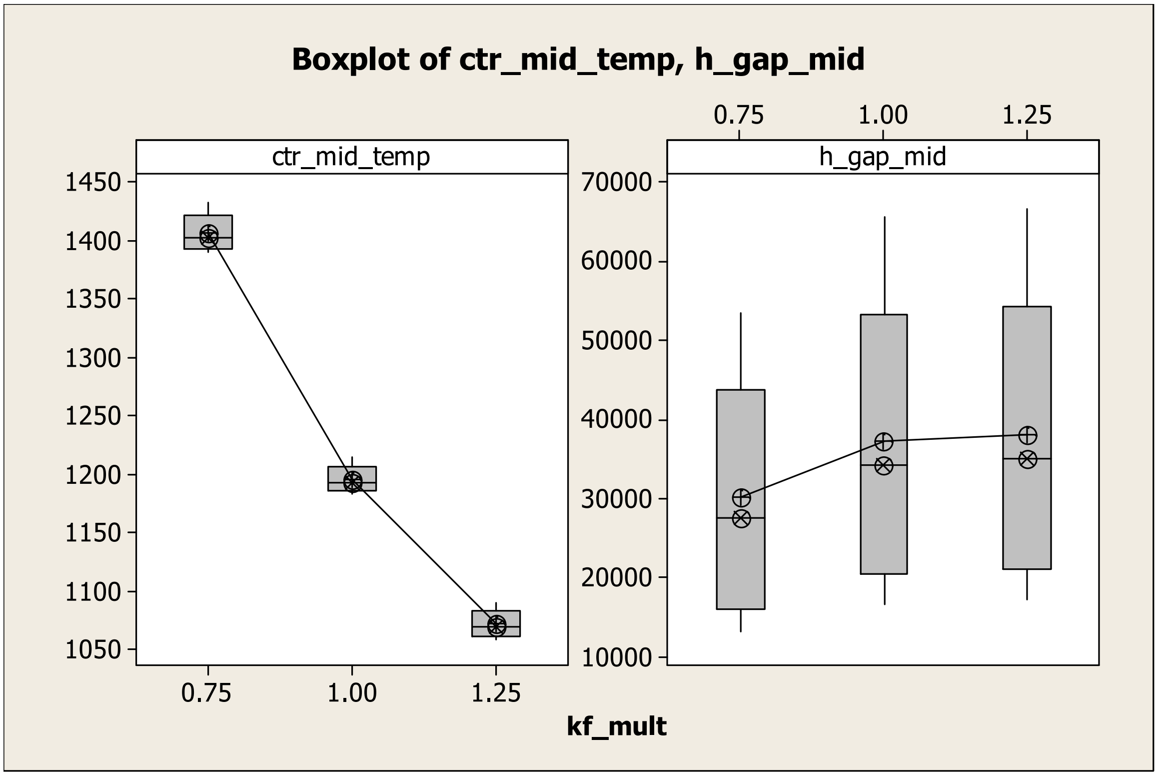

Figure 18: Boxplots based on Fuel thermal conductivity multiplier.

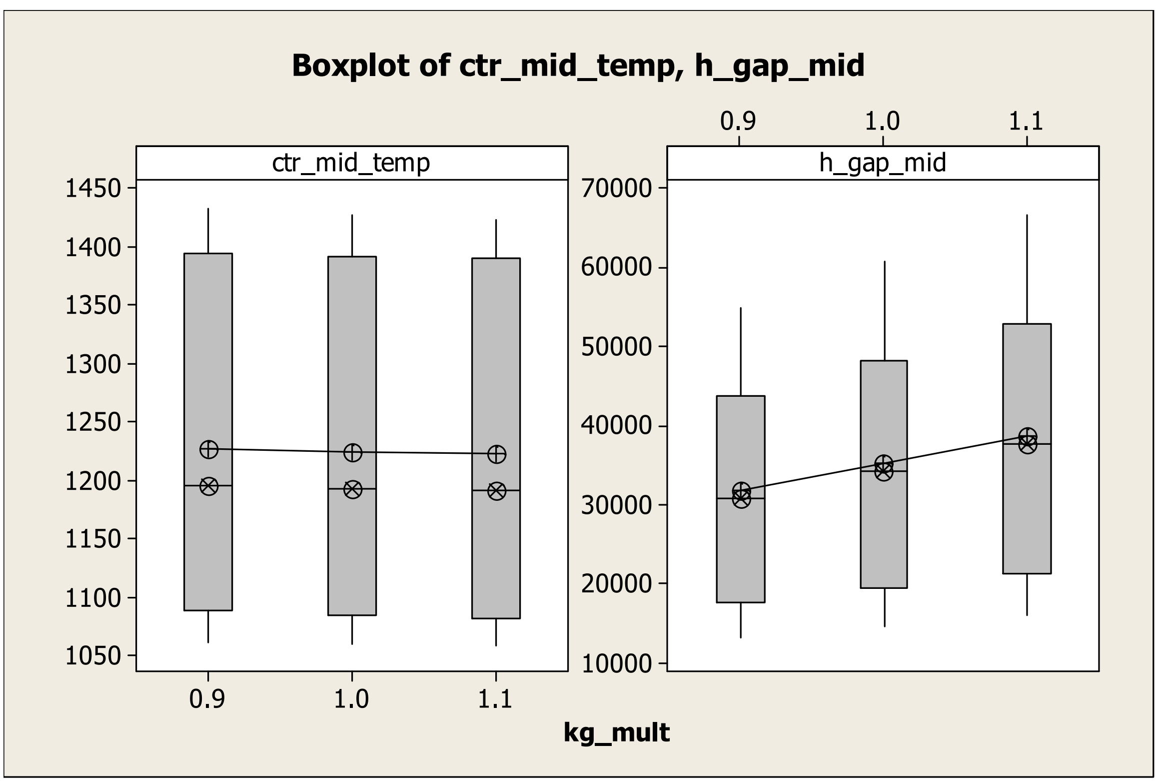

Figure 19: Boxplots based on Gas gap thermal conductivity multiplier.

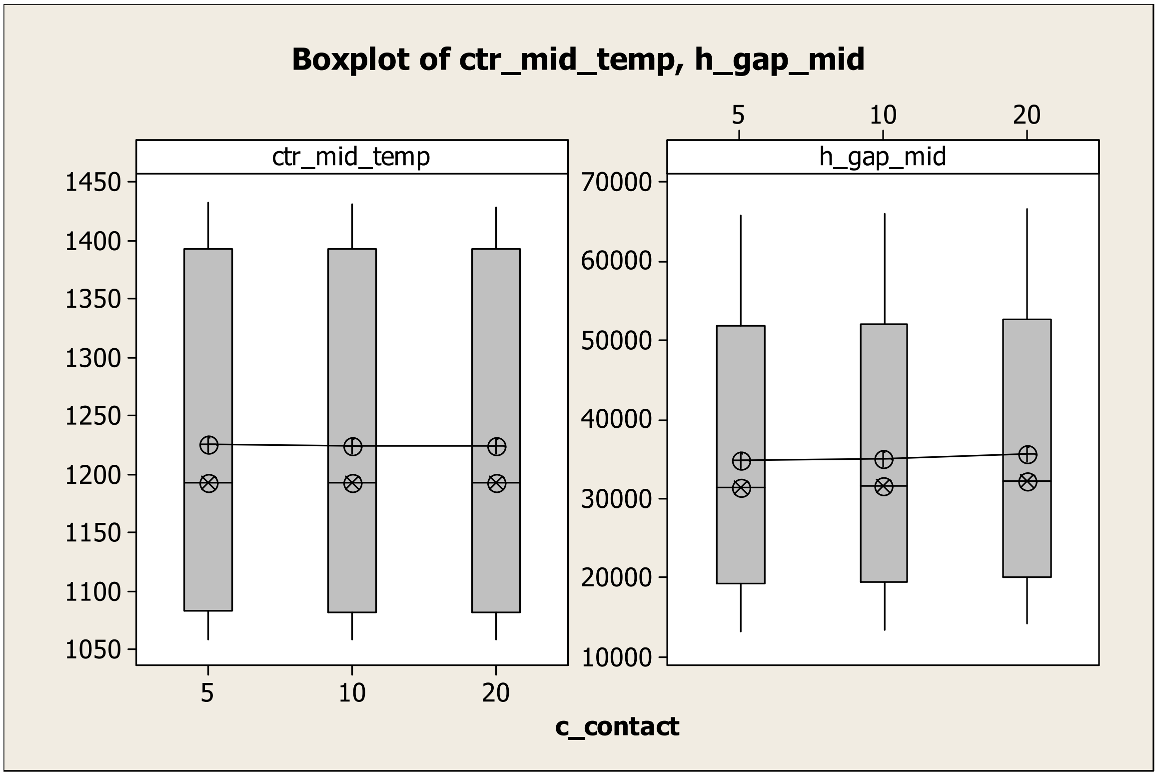

Figure 20: Boxplots based on contact model coefficient.

Discussion of Base Irradiation Case

As the roughness coefficient increases, the variance of the centerline temperature increases slightly, but the variance of gap conductance decreases noticeably, as shown in Figure 16. The opposite is true for the fuel thermal conductivity multiplier: as it increases, the variance of the centerline temperature decreases very slightly but the variance of gap conductance increases significantly, as shown in Figure 18. Note that we see the same behavior after the Risø AN3 experiment is performed (the base irradiation case + experiment). This will be presented below.

One thing that we are not sure about: the response at the fuel thermal conductivity multiplier kf_multiplier = 1.0 and 1.25 are very similar for the gap conductance. This is different than after the experiment, where we saw an increase in the gap_conductance at kf_multiplier = 1.25.

The Kennard temperature jump model coefficient and the contact model coefficient do not exhibit any significant effect on either response. This is a significant finding, as these were parameters of the heat transfer model in the gap that we thought would be significant.

For the centerline temperature, the only variable that has a significant main effect is the fuel thermal conductivity. **For the gap conductance, the roughness coefficient is the most significant.** There are significant, though much smaller, main effects with kf_multiplier and kg_multiplier. Note that for kf_multiplier, we see a difference between the mean at kf_multipler = 0.75 and 1.0 (or 1.25), but not between 1.0 and 1.25. Appendix B provides supporting evidence for these ANOVA results.

Finally, note that the centerline mid-plane temperature in the base irradiation case is much smaller than the base irradiation + experiment case, but the gap conductance is higher. Table 10 shows these differences.

Table 10: Differences between base irradiation and (Base irradiation plus experiment) cases:

	BASE IRRADIATION		**BASE IRRAD PLUS EXPERIMENT**	
	Ctr_mid_temp (K)	H_gap_mid (W/m^2 K).	Ctr_mid_temp (K)	H_gap_mid (W/m^2 K).
MEAN	1224.75	35221.12	2196.41	21107.50
MIN	1058.86	13157.30	1762.38	6499.50
MAX	1432.54	66657.30	2761.34	51571.20

3.5 Sensitivity Analysis: Base Irradiation + Experiment Period

This section outlines the sensitivity of the parameters to the results at the end of the base irradiation + experiment period, at 103788200 seconds after the RISO AN3 experiment was performed, before the power ramp-down. Figure 21 shows the main effects of the parameters on the mean mid-plane centerline temperature, and Figure 22 shows the main effects of the parameters on the mid-plane gap conductance. Note that the thermal conductivity of the fuel is the dominant parameter for the centerline temperature, while the roughness coefficient is the dominant parameter for the gap conductance. However, the thermal conductivity of the fuel plays a more significant role than it does in the baseline case (e.g. compare Figure 15 to Figure 22).

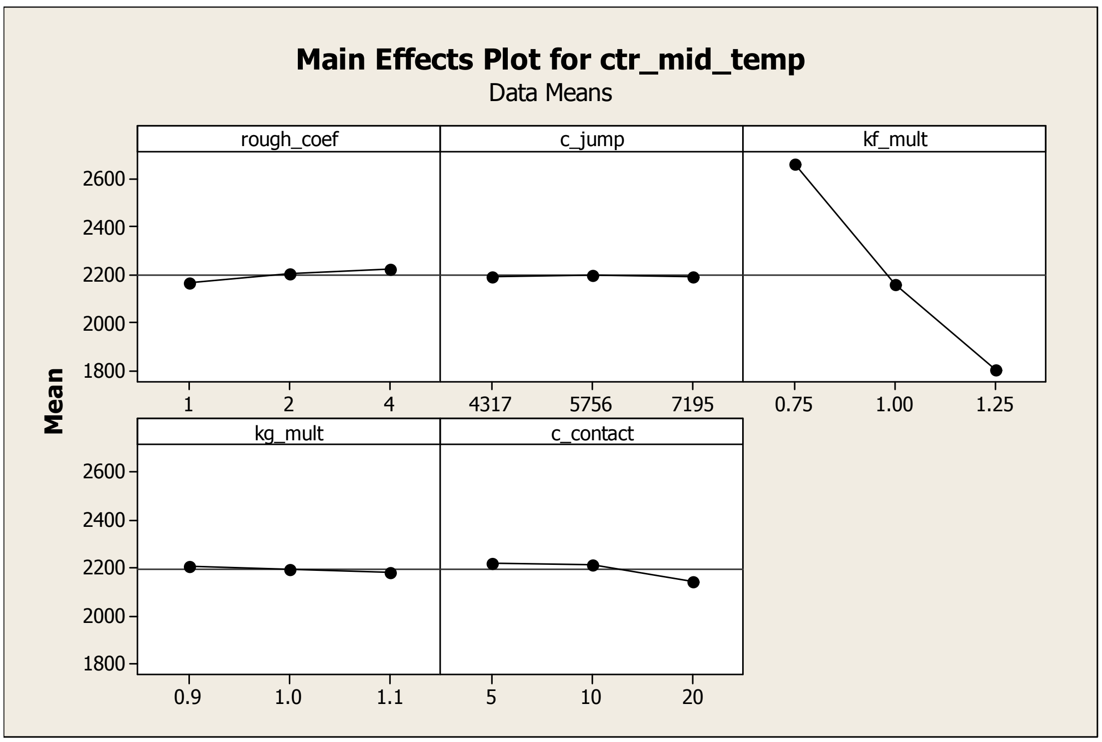

Figure 21. Base irradiation + experiment case:
Main effects for mid-plane centerline temperature (K).

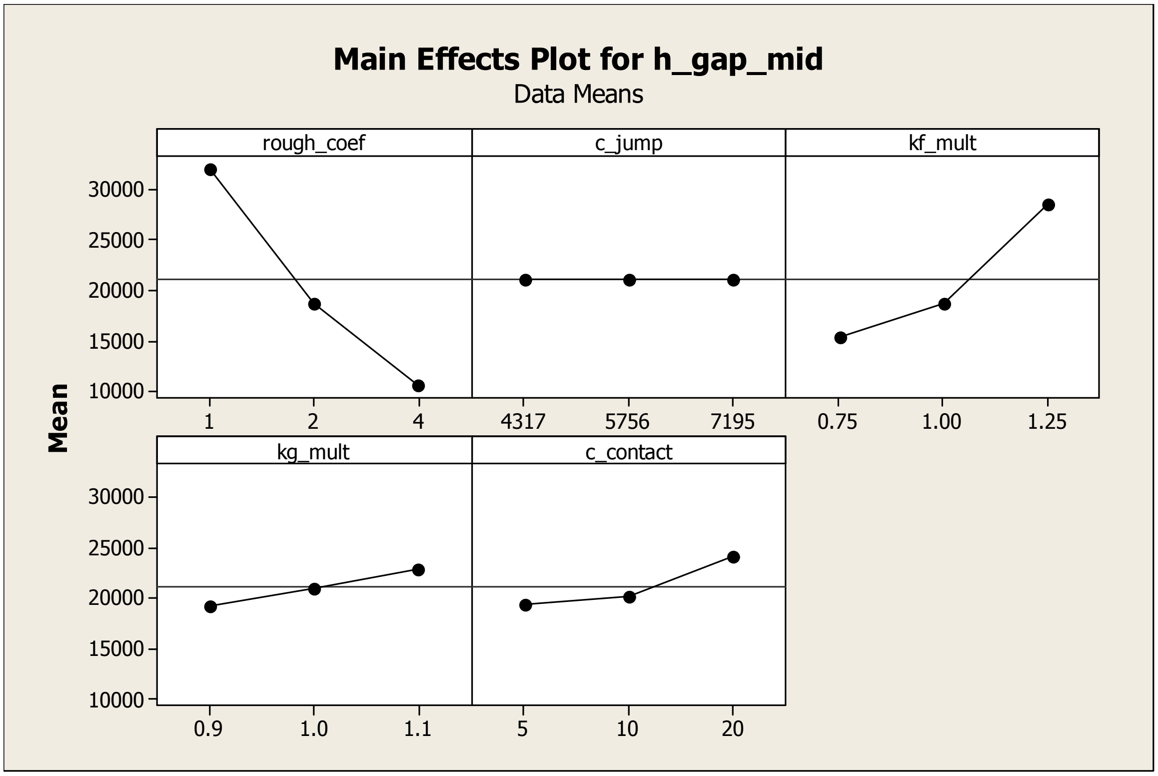

Figure 22. Base irradiation + experiment case:
Main effects for mid-plane gap conductance (W/m^2 K).

The correlation matrices are shown in Tables 11 and 12.

Table 11: Correlation matrix for ctr_mid_temp

	rough_coef	c_jump	kf_mult	kg_mult	c_contact
c_jump	-0.008				
kf_mult	0.063	0			
kg_mult	0.031	0	0.006		
c_contact	-0.123	-0.008	0.063	0.031	
ctr_mid_temp	0.063	0	-0.987	-0.026	-0.094

Table 12: Correlation matrix for h_gap_mid

	rough_coef	c_jump	kf_mult	kg_mult	c_contact
c_jump	-0.008				
kf_mult	0.063	0			
kg_mult	0.031	0	0.006		
c_contact	-0.123	-0.008	0.063	0.031	
ctr_mid_temp	-0.736	-0.003	0.483	0.134	0.174

Figures 23-27 show boxplots of the data, across the various levels of the parameters. This provides more detail than the main effects plots. There is more detail about the sensitivity analysis, especially the Analysis of Variance (ANOVA) results, in Appendix C.

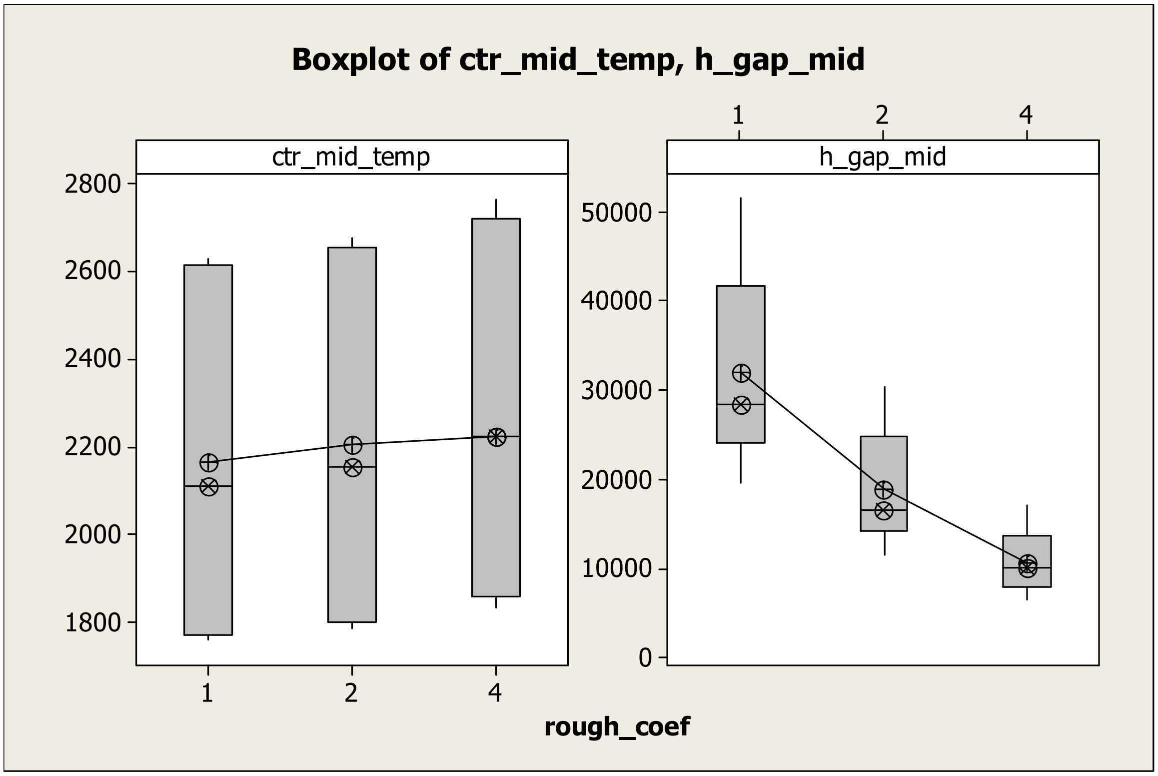

Figure 23: Boxplots based on roughness coefficient.

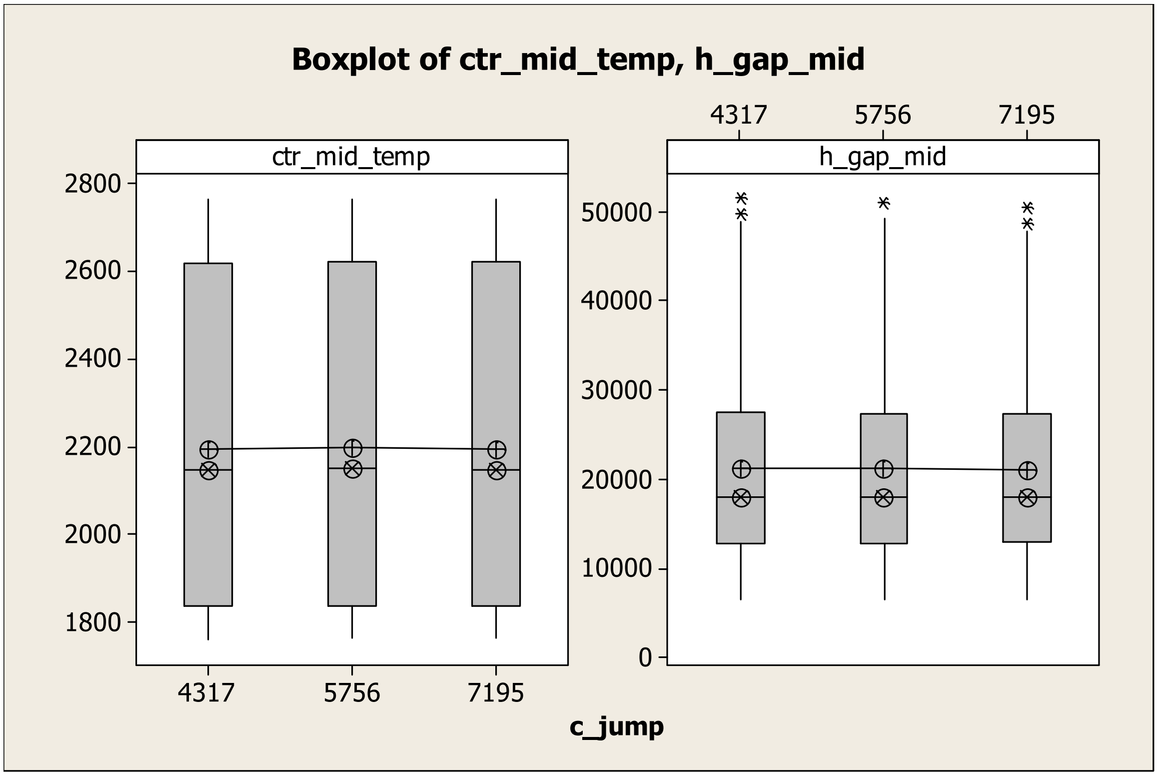

Figure 24: Boxplots based on Kennard temperature jump model coefficient.

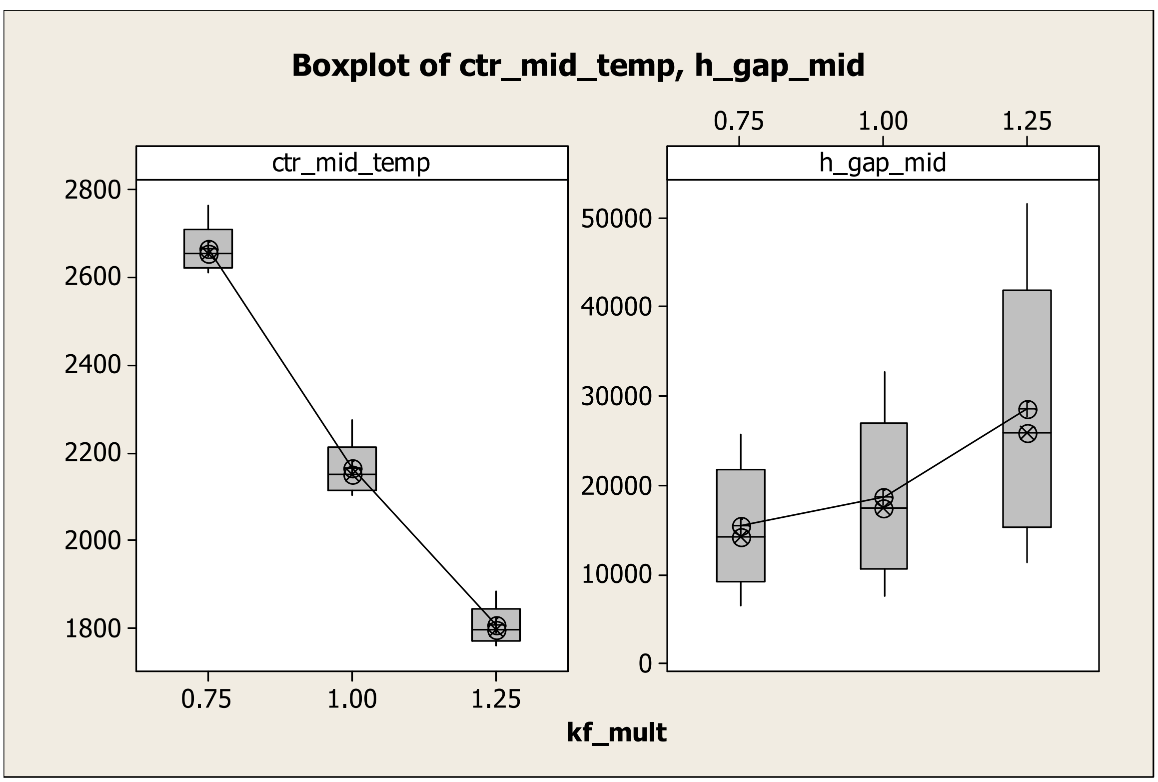

Figure 25: Boxplots based on Fuel thermal conductivity multiplier.

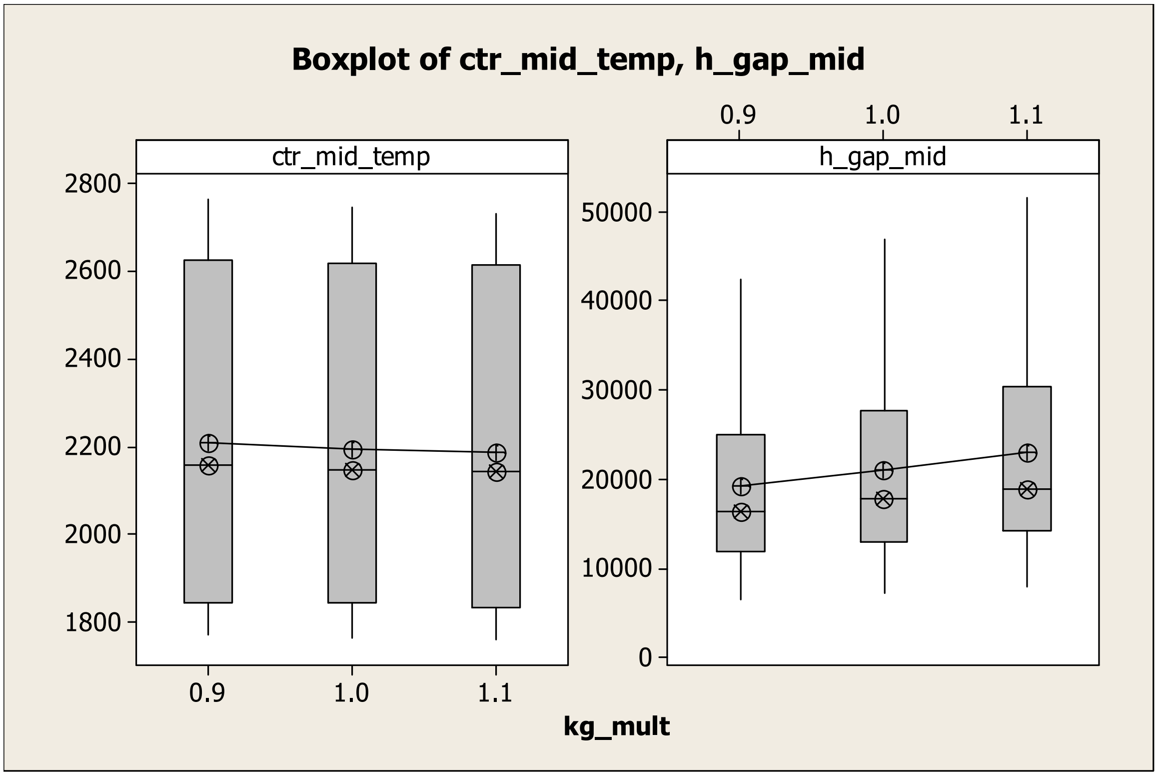

Figure 26: Boxplots based on Gas gap thermal conductivity multiplier.

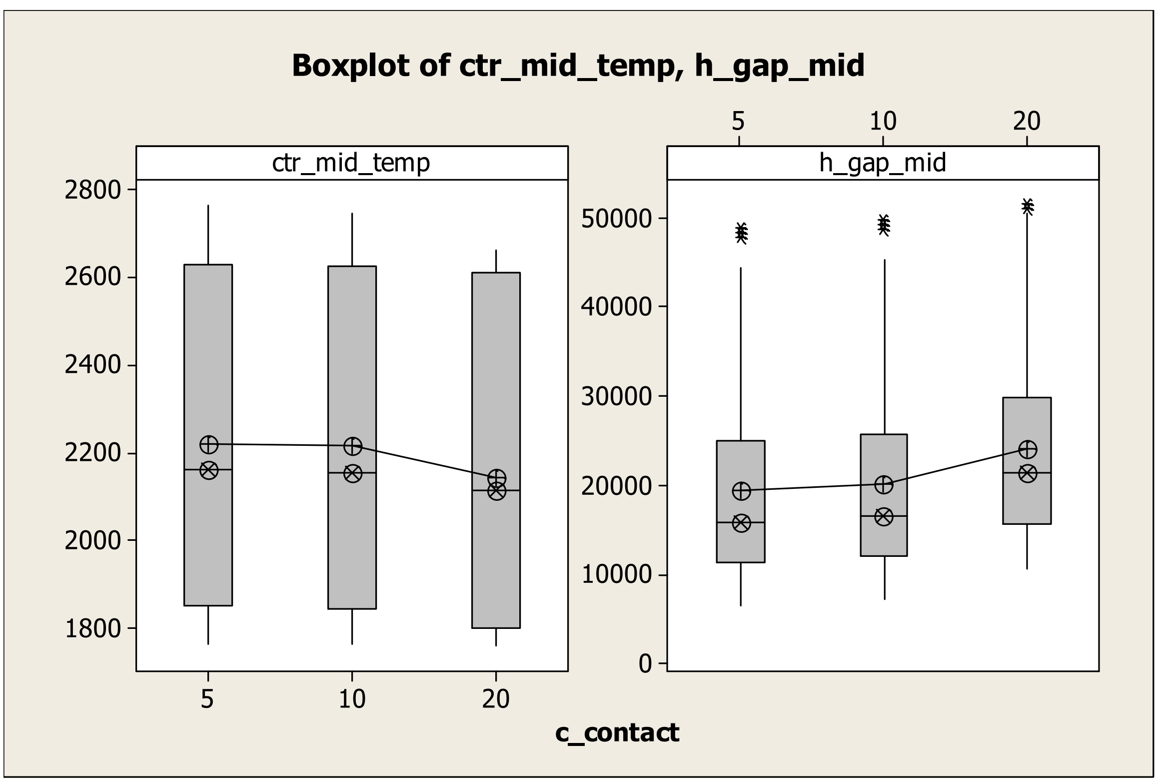

Figure 27: Boxplots based on contact model coefficient.

Discussion of Base Irradiation + Experiment Case

For the centerline temperature, the only variable that has a significant main effect is the fuel thermal conductivity multiplier. This is shown in the main effects and boxplots above (Figures 21 and 25) and the ANOVA results in Appendix C. **For the gap conductance, both the roughness coefficient and the fuel thermal conductivity multiplier are significant.**

The Kennard temperature jump model coefficient does not exhibit any significant effect on either response.

Similar to the base irradiation case: As the roughness coefficient increases, the variance of the centerline temperature increases slightly, but the variance of gap conductance decreases noticeably (Figure 23). The opposite is true for the fuel thermal conductivity multiplier: as it increases, the variance of the centerline temperature decreases very slightly but the variance of gap conductance increases significantly (Figure 25).

NOTE: We did conduct a main effects analysis after power-down, at the very end of the simulation. We are not showing the results here since they are very similar to these results before the power-down. The major difference between these results and the results at the end of the simulation after power-down is that the roughness coefficient and the fuel thermal conductivity have switched the order of their importance on the gap conductance. After power-down, the fuel thermal conductivity is the most important parameter. But in these results before power-down, the roughness coefficient is the most important variable for the gap conductance.

Finally, note that c_contact did have a small but significant main effect on the gap conductance. If you look at the ANOVA results in Appendix C, the p-value is 0.026 for the gap conductance and c_contact. This implies that we cannot say all three means (e.g. the mean at c_contact =5, 10, or 20) are the same. If we were only looking at 5 and 10 we could not say they are statistically significantly different, but the mean of the gap conductance at c_contact=5 and c_contact = 20 are different.

4. CONCLUSIONS

In this report, we present a detailed sensitivity analysis of the heat transfer model used in the BISON code to model heat transfer in the gap between the fuel rod and the cladding. We performed three different case studies. First, we examined the analytic behavior of the gap heat transfer by developing a standalone model of the governing equations. The second study involved the sensitivity of the model parameters at the beginning of life. The third study involved the sensitivity of the model parameters in highly irradiated fuel.

In the study of the analytic model, we found the following:

- Varying the roughness coefficient over the specified range was the most significant factor among the five parameters for all gap widths.
- Varying the emissivity over its entire range of possibility has only a very small impact, demonstrating that radiation heat transfer is relatively weak under these conditions. Only with a large gap width, where the surface temperatures are several hundred degrees higher, do we begin to see some noticeable impact.
- The gas thermal conductivity can be important as the gap width becomes large. This directly reflects that the thermal resistance due to thermal conduction across the gap scales linearly with the gap width.

Note that fuel thermal conductivity does not affect the gap heat transfer directly, so this parameter is not a factor in this assessment.

We used the Halden IFA-431 rod 1 to study the sensitivity of the BISON heat transfer model parameters during beginning of life. We found the following:

- The thermal conductivity of the fuel was the most significant variable influencing the temperature at the upper and lower thermocouples, followed by the roughness coefficient.
- The thermal conductivity of the gas in the gap had a small effect, and the Kennard temperature jump coefficient had very little influence on the centerline temperatures of the thermocouples.
- Detailed analyses of the parameter influences are shown in Table 6.
- The power profile for this Halden rod was complicated with significant power cycling. We ran a smooth power profile that was similar in overall increase in fuel rod temperatures. The sensitivity analysis with the simpler power profile gave very similar results to the actual power profile and required less run-time (BISON execution time).

We used the RISO AN3 rod to study the sensitivity of the BISON gap heat transfer model parameters for highly irradiated rods. We looked at two times: a time of baseline irradiation (approximately 1200 days when the rod was at fairly constant power levels) and a final experimental time of 3 days when the rod was in the experimental reactor. Our findings:

- For the mid-plane centerline temperature, the only variable that has a significant main effect is the fuel thermal conductivity multiplier. For the mid-plane gap conductance, both the roughness coefficient and the fuel thermal conductivity multiplier are significant. This finding is true for both the baseline irradiation and for the baseline+experiment cases.

- The Kennard temperature jump model coefficient does not exhibit any significant effect on either response (centerline temperature or gap conductance). This finding is true for both the baseline irradiation and for the baseline+experiment cases.
- The contact model coefficient did not have an effect either response in the baseline irradiation case. It had a very small effect only on the gap conductance in the baseline+experiment case.
- The thermal conductivity of the gas in the gap had a small effect on the gas gap conductance for both baseline and baseline+experiment. It did not affect the centerline temperature, however.
- The centerline temperatures were significantly higher (~1000 degrees higher) for the baseline+experiment case than for the baseline case due to the much higher power during the experiment. However, compared with the baseline case, the gap gas conductance was in the mean ~ 40 % lower for the baseline+experiment case.

Comment [RS]: This concerns me as I can't rationalize this result. We need to discuss this with INL.

In summary, the thermal conductivity of the fuel dominated the results in the Halden and Risø cases we studied, both at beginning of life and in highly irradiated cases. This is a significant finding, as these results suggest that for the models currently in Bison, the complicated gap heat transfer modeling is not nearly as important as may have been assumed. It points to the need to have accurate estimates of the fuel thermal conductivity when running further BISON studies.

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APPENDIX A: LISTING OF THE GAPCLADHT FORTRAN CODE

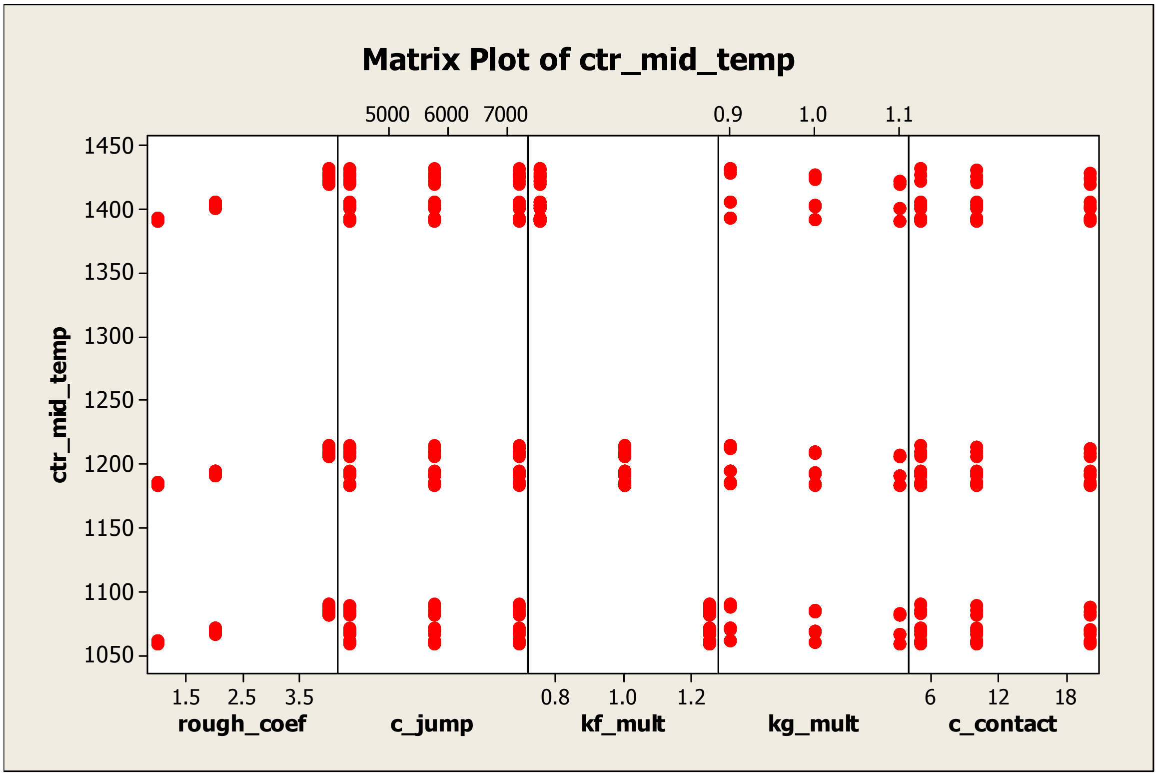
```
! ==========================================================================================
!   gapcladHT.f90
!
!   Heat transfer across the gap and clad of a fuel rod as modeled in BISON (See BISON
!   Theory manual). It will be used as a simple surrogate for BISON to help set up a
!   sensitivity study.
!   Created by Schmidt, Rodney C
! ==========================================================================================
PROGRAM gapclad

  USE input_mod
  IMPLICIT NONE

! ==========================================================================================
! ==========================================================================================
  WRITE(*,*) "***************************"
  WRITE(*,*) "     Program gapclad      "
  WRITE(6,*) "***************************"

  CALL read_input_file

  CALL solve_problem

END PROGRAM gapclad


! ==========================================================================================
SUBROUTINE solve_problem

  USE input_mod
  USE var_mod
  IMPLICIT NONE

  ! Variable declarations

  INTEGER :: DBUG=0     ! Debug flag for printing extra output
  INTEGER :: IT         ! Main iteration index
  INTEGER :: ITMAX = 25 ! Max numbed of iterations
  REAL    :: TOL=2.e-5  ! Non-linear Convergence Tolerance
  REAL    :: TCHG       ! Change in T1 between iterations
  REAL    :: T1old      ! Previous iterate value of T1
  REAL    :: Rgap       ! Thermal resistance of the gap
  REAL    :: Rcld       ! Thermal resistance of the clad

! ==========================================================================================
! ==========================================================================================
  WRITE(6,*) "Subroutine solve_problem"

  ! Initialize temperatures
  T1 = TBC
  T2 = TBC
  T3 = TBC

  DO IT=1,ITMAX          ! Main nonlinear iteration loop

    T1old = T1
    CALL update(Rgap, Rcld)
    T1 = T3 + qflx*(Rgap + Rcld)
    T2 = T3 + qflx*Rcld
```

```
    TCHG = ABS(T1-T1old)
    IF(TCHG .le. TOL) EXIT  ! Convergence
    !WRITE(6,*) IT, T1, T1old
  ENDDO

  IF(IT.gt.ITMAX) THEN
    WRITE(6,*) "*** Warning: Convergence criteria not met in solve_problem"
    WRITE(6,9) "The change in T1 temperature over the last update =", TCHG
    WRITE(6,99) "ITMAX = ", ITMAX
  ELSE
    WRITE(6,99) " Iterations to converge =", IT
  ENDIF

  WRITE(6,9) " T3 = ", T3
  WRITE(6,9) " T2 = ", T2
  WRITE(6,9) " T1 = ", T1

!9  FORMAT(a,F9.3)
9  FORMAT(a,F12.6)
99 FORMAT(a,I3)
! ==============================================================================
END Subroutine solve_problem



! ==============================================================================
SUBROUTINE update(Rgap, Rcld)

  USE input_mod
  USE var_mod
  IMPLICIT NONE

  ! Variable declarations
  REAL    :: Rgap       ! Thermal resistance of the gap
  REAL    :: Rcld       ! Thermal resistance of the clad
  REAL    :: TG         ! avg gap temperature (T1+T2)/2
  REAL    :: TC         ! avg clad temperature (T2+T3)/2

! ==============================================================================
! ==============================================================================

  ! ----------------------
  ! Model for conduction-based heat transfer coefficient across the gap
     TG = (T1+T2)/2.
     TC = (T2+T3)/2.

     ! Compute thermal conductivity of the gas in the gap
     ! k_g = 0.081594 + 2.4147e-4*TC  ! Pure helium, W/m K
     k_g = 0.0468 + 3.81e-4*TC - 6.79e-8*TC*TC ! Bejan 1993
     k_g = k_g * k_g_mult  ! gas TC multipliear (default 1.0)

     ! Compute jump distance
     CALL jmp_dist(P_p, TG, k_g, g12)
     g12 = g12 * ken_mult ! Kennard model multiplier (default 1.0)

  h_g = k_g / (d_g + C_r*r12 + g12)
  !WRITE(6,*) "h_g =", h_g

  ! ----------------------
  ! Model for linearized radiation-based heat transfer coeficient across the gap
  e_1 = max(e_1,1.e-8) ! prevent divide by zero for zero emiss.
```

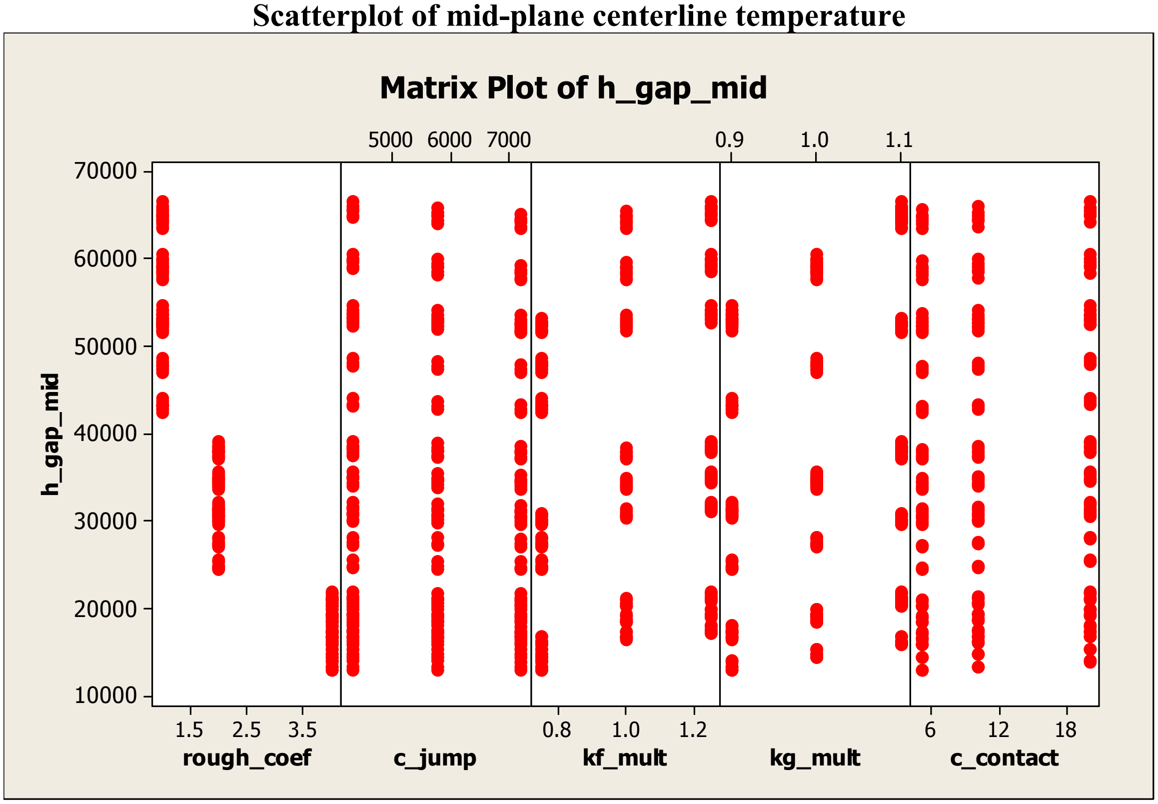
```
 e_2 = max(e_2,1.e-8) ! prevent divide by zero for zero emiss.
 h_r = sig*(T1*T1 + T2*T2)*(T1+T2)/ ( 1./e_1 + 1./e_2 + 1.)
 !WRITE(6,*) "h_r =", h_r

 ! ----------------------
 ! Model for increased conductance due to solid-solid contact

 IF(P_c .le. 1.0) THEN
   h_s = 0.0
 ELSE
   h_s = 0.0  ! replace with model
 ENDIF

 ! ----------------------
 ! Compute the total thermal resistance of that gap due to each contribution

 Rgap = 1./(h_g + h_s + h_r)
 !WRITE(6,*) "Rgap =", Rgap

 ! ----------------------
 ! Compute the thermal resistance of the clad  (Assumed Zircaloy)

 k_c = 7.511 + 0.02088*TC - 1.45e-5*TC*TC + 7.688e-9*TC*TC*TC ! MELPROG Models and Corr.
 k_c = k_c * k_c_mult  ! clad TC multipliear (default 1.0)

 Rcld = d_c/k_c
 !WRITE(6,*) "Rcld =", Rcld

! ==============================================================================
END Subroutine update



! ==============================================================================
SUBROUTINE jmp_dist(P_p, TG, k_g, g12)
!
! Compute the Temperature jump distance using "Kennard's model based on a review
! by Lanning [70]" (See BISON Theory Manual pg. 51). Here implimented for
! pure helium.

 IMPLICIT NONE

 ! Variable declarations
 REAL    :: g12      ! Temperature jump distance (m)
 REAL    :: TG       ! Avg gas temperature (T1+T2)/2
 REAL    :: P_p      ! Thermodynamic pressure of gas in the fuel pin gap (units??)
 REAL    :: k_g      ! Therm. Conductivity of the gas in the gap

 REAL    :: ahe      ! accomodation coefficient for helium
 REAL    :: amix     ! accomodation coefficient for mixture
 REAL    :: M_he=4.0  ! Molecular weight of helium   =   4.003 g/m
 REAL    :: uconv1 = 2.3901e-3   ! W/m-K to cal/sec-cm-K
 REAL    :: uconv2 = 10.0        ! Pa to dynes/cm^2
 REAL    :: uconv3 = 0.01        ! cm to m
 REAL    :: cfac

!  REAL   :: M_xe    ! Molecular weight of zenon    = 131.293 g/m
!  REAL   :: M_xe    ! Molecular weight of mixture
! ==============================================================================
! ==============================================================================

 ahe = 0.425 - 2.3e-4*TG   ! (per Eq. 13.4)
```

```
  amix = ahe    ! 100% helium - per Eq. 13.6

  cfac = uconv1*uconv3/uconv2 ! conversion factor

  g12 = cfac * 5756.* ((2.-amix)/amix) * (k_g*SQRT(TG)/P_p) / SQRT(1./M_he)

!  WRITE(6,*) "DEBUG:  P_p =", P_p
!  WRITE(6,*) "DEBUG:   TG =", TG
!  WRITE(6,*) "DEBUG:  k_g =", k_g
!  WRITE(6,*) "DEBUG: amix =", amix
  WRITE(6,*) "DEBUG:  g12 =", g12
!  WRITE(6,*) " "
! ==========================================================================
END Subroutine jmp_dist
```

APPENDIX B: ADDITIONAL SENSITIVITY ANALYSIS RESULTS FOR BASELINE IRRADATION CASE



Scatterplot of mid-plane centerline temperature



Scatterplot of mid-plane heat conductance

Analysis of Variance (ANOVA) results:
The p-value indicates if there are significant differences in the means across levels of a parameter. One needs a p-value less than 0.05 to be significant. The closer the p-value is to zero, the more significant the effect, the closer the P-value is to one, the less significant.

One-way ANOVA: ctr_mid_temp versus rough_coef

```
Source       DF       SS     MS     F      P
rough_coef    2    33632  16816  0.86  0.422
Error       240  4666225  19443
Total       242  4699856

S = 139.4   R-Sq = 0.72%   R-Sq(adj) = 0.00%


                           Individual 95% CIs For Mean Based on
                           Pooled StDev
Level   N    Mean  StDev  -------+---------+---------+---------+--
1      81  1212.1  137.7  (-----------*-----------)
2      81  1221.7  138.9     (------------*-----------)
4      81  1240.4  141.6             (-----------*-----------)
                          -------+---------+---------+---------+--
                              1200      1225      1250      1275

Pooled StDev = 139.4
```

One-way ANOVA: ctr_mid_temp versus c_jump

```
Source   DF       SS     MS     F      P
c_jump    2        2      1  0.00  1.000
Error   240  4699854  19583
Total   242  4699856

S = 139.9   R-Sq = 0.00%   R-Sq(adj) = 0.00%


                           Individual 95% CIs For Mean Based on
                           Pooled StDev
Level   N    Mean  StDev  ----+---------+---------+---------+-----
4317   81  1224.6  139.9  (------------------*-------------------)
5756   81  1224.8  139.9  (------------------*-------------------)
7195   81  1224.9  139.9  (-------------------*------------------)
                          ----+---------+---------+---------+-----
                           1200      1216      1232      1248

Pooled StDev = 139.9
```

One-way ANOVA: ctr_mid_temp versus kf_mult

```
Source    DF       SS       MS         F      P
kf_mult    2  4664231  2332116  15711.05  0.000
Error    240    35625      148
Total    242  4699856

S = 12.18   R-Sq = 99.24%   R-Sq(adj) = 99.24%
```

```
                              Individual 95% CIs For Mean Based on
                              Pooled StDev
Level   N    Mean  StDev  ---+---------+---------+---------+------
0.75   81  1407.1   14.5                                   (*
1.00   81  1195.6   10.9              (*
1.25   81  1071.5   10.7  *
                          ---+---------+---------+---------+------
                          1100      1200      1300      1400

Pooled StDev = 12.2
```

One-way ANOVA: ctr_mid_temp versus kg_mult

```
Source    DF       SS     MS     F      P
kg_mult    2     1014    507  0.03  0.974
Error    240  4698842  19579
Total    242  4699856

S = 139.9   R-Sq = 0.02%   R-Sq(adj) = 0.00%


                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level   N    Mean  StDev  ----+---------+---------+---------+-----
0.9    81  1227.3  140.3    (---------------*--------------)
1.0    81  1224.6  139.9   (--------------*---------------)
1.1    81  1222.3  139.5  (--------------*--------------)
                          ----+---------+---------+---------+-----
                           1200      1220      1240      1260

Pooled StDev = 139.9
```

One-way ANOVA: ctr_mid_temp versus c_contact

```
Source       DF       SS     MS     F      P
c_contact     2       30     15  0.00  0.999
Error       240  4699826  19583
Total       242  4699856

S = 139.9   R-Sq = 0.00%   R-Sq(adj) = 0.00%


                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level   N    Mean  StDev  ----+---------+---------+---------+-----
 5     81  1225.1  140.1   (------------------*------------------)
10     81  1224.8  140.0  (-------------------*------------------)
20     81  1224.3  139.8  (------------------*------------------)
                          ----+---------+---------+---------+-----
                           1200      1216      1232      1248

Pooled StDev = 139.9
```

One-way ANOVA: h_gap_mid versus rough_coef

```
Source       DF           SS           MS        F      P
rough_coef    2  57996613399  28998306700  1181.36  0.000
Error       240   5891188815     24546620
Total       242  63887802214

S = 4954   R-Sq = 90.78%   R-Sq(adj) = 90.70%


                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level   N   Mean  StDev  ---+---------+---------+---------+------
1      81  55390   7011                                     (*)
2      81  32411   4268                 (*)
4      81  17862   2504   (*)
                          ---+---------+---------+---------+------
                         20000     30000     40000     50000

Pooled StDev = 4954
```

One-way ANOVA: h_gap_mid versus c_jump

```
Source   DF           SS         MS     F      P
c_jump    2     10690796    5345398  0.02  0.980
Error   240  63877111418  266154631
Total   242  63887802214

S = 16314   R-Sq = 0.02%   R-Sq(adj) = 0.00%


                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level   N   Mean  StDev  ---+---------+---------+---------+------
4317   81  35479  16531      (-----------------*-----------------)
5756   81  35220  16312    (-----------------*-----------------)
7195   81  34965  16098   (-----------------*-----------------)
                          ---+---------+---------+---------+------
                         32000     34000     36000     38000

Pooled StDev = 16314
```

One-way ANOVA: h_gap_mid versus kf_mult

```
Source    DF           SS          MS     F      P
kf_mult    2   3068874043  1534437021  6.06  0.003
Error    240  60818928172   253412201
Total    242  63887802214

S = 15919   R-Sq = 4.80%   R-Sq(adj) = 4.01%


                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level   N   Mean  StDev  ---+---------+---------+---------+------
0.75   81  30216  13864   (--------*-------)
1.00   81  37329  16794                     (-------*--------)
1.25   81  38118  16911                       (-------*--------)
                          ---+---------+---------+---------+------
```

```
                         28000     32000     36000     40000

Pooled StDev = 15919
```

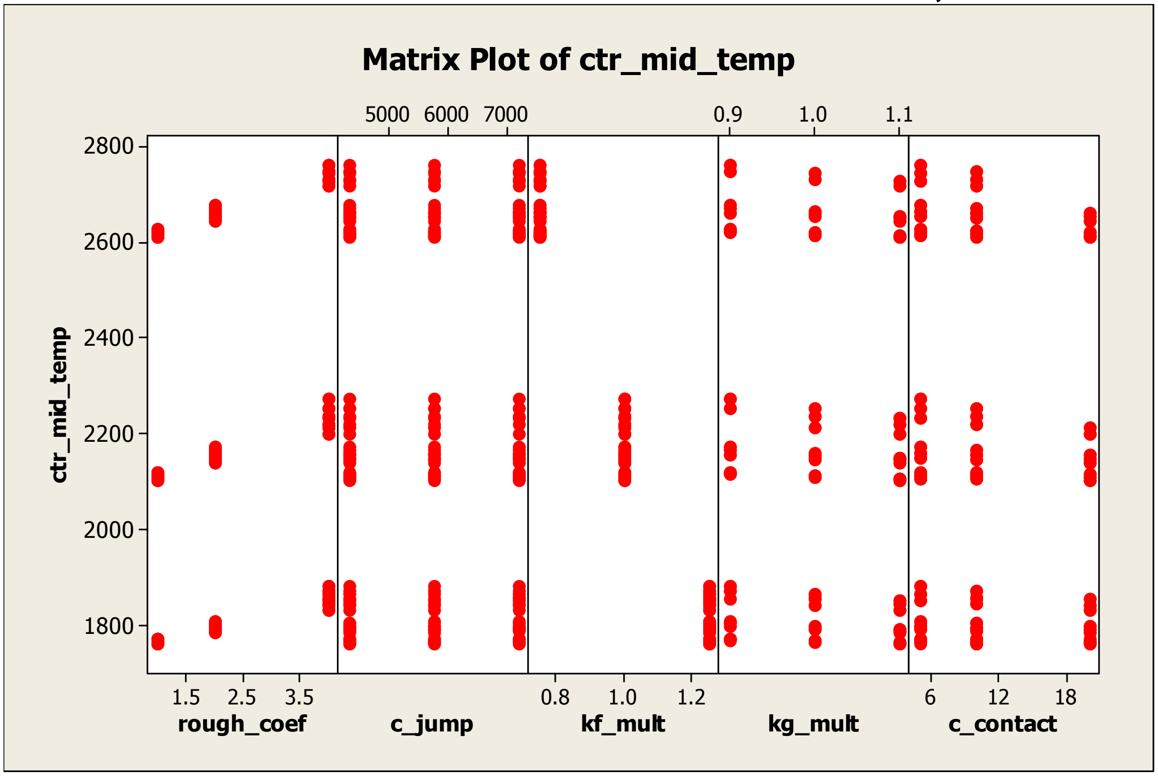
One-way ANOVA: h_gap_mid versus kg_mult

```
Source    DF           SS         MS     F      P
kg_mult    2   1914746659  957373329  3.71  0.026
Error    240  61973055555  258221065
Total    242  63887802214

S = 16069   R-Sq = 3.00%   R-Sq(adj) = 2.19%


                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level   N   Mean  StDev  ---------+---------+---------+---------+
0.9    81  31783  14418  (---------*---------)
1.0    81  35221  16016            (---------*---------)
1.1    81  38659  17614                     (---------*----------)
                         ---------+---------+---------+---------+
                             31500     35000     38500     42000

Pooled StDev = 16069
```

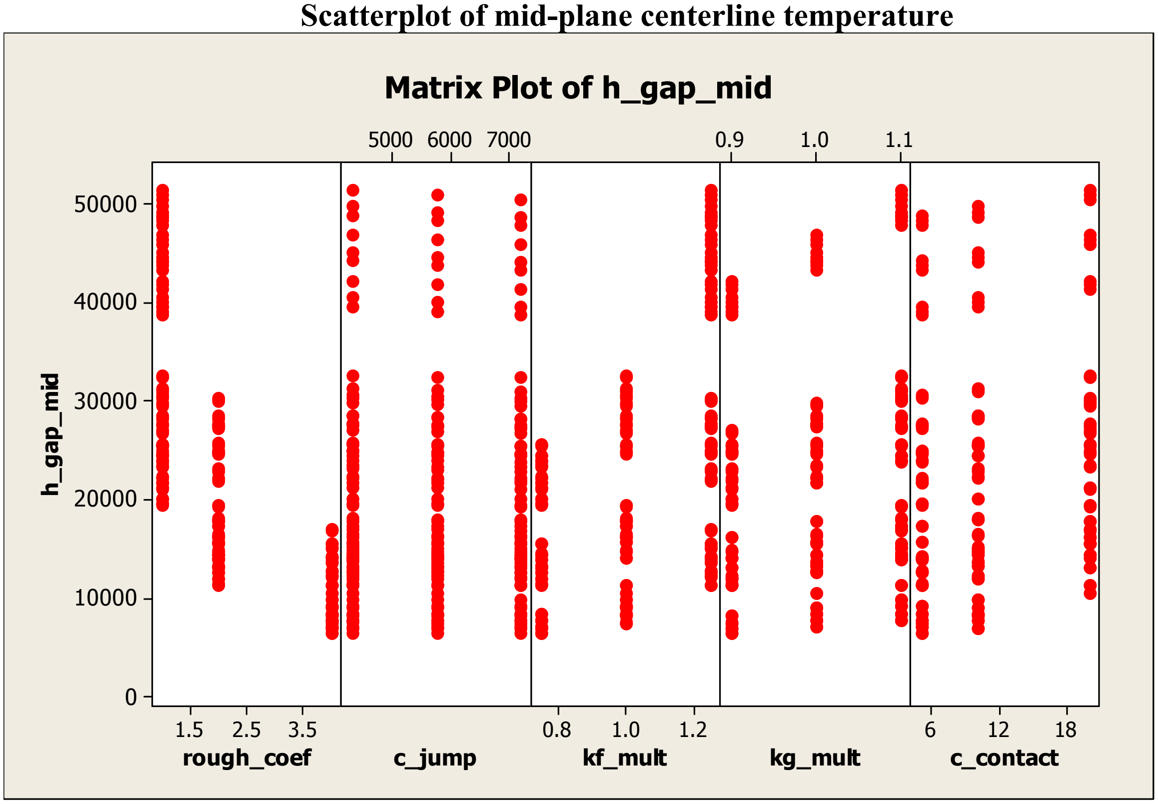
One-way ANOVA: h_gap_mid versus c_contact

```
Source      DF           SS         MS     F      P
c_contact    2     30870098   15435049  0.06  0.944
Error      240  63856932116  266070550
Total      242  63887802214

S = 16312   R-Sq = 0.05%   R-Sq(adj) = 0.00%


                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level   N   Mean  StDev  ----+---------+---------+---------+-----
 5     81  34840  16316  (-----------------*-----------------)
10     81  35126  16313    (-----------------*-----------------)
20     81  35697  16306       (-----------------*-----------------)
                         ----+---------+---------+---------+-----
                         32000     34000     36000     38000

Pooled StDev = 16312
```

APPENDIX C: ADDITIONAL SENSITIVITY ANALYSIS RESULTS FOR BASELINE IRRADIATION CASE+EXPERIMENT, RISO AN3



Scatterplot of mid-plane centerline temperature



Scatterplot of mid-plane gap conductance

Analysis of Variance (ANOVA) results:

The p-value indicates if there are significant differences in the means across levels of a parameter. One needs a p-value less than 0.05 to be significant. The closer the p-value is to zero, the more significant the effect, the closer the P-value is to one, the less significant.

One-way ANOVA: ctr_mid_temp versus rough_coef

```
Source       DF        SS      MS     F      P
rough_coef    2    132094   66047  0.53  0.591
Error       226  28333028  125367
Total       228  28465122

S = 354.1   R-Sq = 0.46%   R-Sq(adj) = 0.00%


                           Individual 95% CIs For Mean Based on
                           Pooled StDev
Level   N    Mean  StDev   --+---------+---------+---------+-------
1      81  2165.8  351.5    (------------*------------)
2      81  2204.2  356.3          (------------*------------)
4      67  2224.0  354.5            (-------------*-------------)
                           --+---------+---------+---------+-------
                           2100      2160      2220      2280

Pooled StDev = 354.1
```

One-way ANOVA: ctr_mid_temp versus c_jump

```
Source   DF        SS      MS     F      P
c_jump    2      1076     538  0.00  0.996
Error   226  28464046  125947
Total   228  28465122

S = 354.9   R-Sq = 0.00%   R-Sq(adj) = 0.00%


                           Individual 95% CIs For Mean Based on
                           Pooled StDev
Level   N    Mean  StDev   -------+---------+---------+---------+--
4317   77  2194.7  354.2   (---------------*---------------)
5756   76  2199.5  354.2    (---------------*---------------)
7195   76  2195.1  356.3   (---------------*---------------)
                           -------+---------+---------+---------+--
                               2150      2200      2250      2300

Pooled StDev = 354.9
```

One-way ANOVA: ctr_mid_temp versus kf_mult

```
Source    DF        SS        MS        F      P
kf_mult    2  27973491  13986745  6429.62  0.000
Error    226    491631      2175
Total    228  28465122

S = 46.64   R-Sq = 98.27%   R-Sq(adj) = 98.26%
```

```
                              Individual 95% CIs For Mean Based on
                              Pooled StDev
Level   N    Mean  StDev  --------+---------+---------+---------+-
0.75   72  2663.8   47.9                                    (*
1.00   77  2164.4   52.9                 (*
1.25   80  1806.5   38.3  *)
                          --------+---------+---------+---------+-
                               2000      2250      2500      2750

Pooled StDev = 46.6
```

One-way ANOVA: ctr_mid_temp versus kg_mult

```
Source    DF        SS      MS     F      P
kg_mult    2     20422   10211  0.08  0.922
Error    226  28444700  125862
Total    228  28465122

S = 354.8   R-Sq = 0.07%   R-Sq(adj) = 0.00%


                              Individual 95% CIs For Mean Based on
                              Pooled StDev
Level   N    Mean  StDev  ---------+---------+---------+---------+
0.9    74  2209.1  359.9       (----------------*----------------)
1.0    77  2194.6  353.9    (----------------*----------------)
1.1    78  2186.1  350.6  (----------------*----------------)
                          ---------+---------+---------+---------+
                                2150      2200      2250      2300

Pooled StDev = 354.8
```

One-way ANOVA: ctr_mid_temp versus c_contact

```
Source      DF        SS      MS     F      P
c_contact    2    274201  137100  1.10  0.335
Error      226  28190921  124739
Total      228  28465122

S = 353.2   R-Sq = 0.96%   R-Sq(adj) = 0.09%


                              Individual 95% CIs For Mean Based on
                              Pooled StDev
Level   N    Mean  StDev  ------+---------+---------+---------+---
 5     81  2221.5  360.5              (-----------*-----------)
10     81  2215.7  359.0             (------------*-----------)
20     67  2142.7  336.8  (-----------*-----------)
                          ------+---------+---------+---------+---
                             2100      2170      2240      2310

Pooled StDev = 353.2
```

One-way ANOVA: h_gap_mid versus rough_coef

```
Source       DF           SS          MS       F      P
rough_coef    2  17477910680  8738955340  176.91  0.000
Error       226  11163978209    49398134
Total       228  28641888889
```

```
S = 7028   R-Sq = 61.02%   R-Sq(adj) = 60.68%


                           Individual 95% CIs For Mean Based on
                           Pooled StDev
Level   N   Mean  StDev  -------+---------+---------+---------+--
1      81  32070   9970                                 (-*-)
2      81  18781   5669              (-*-)
4      67  10666   3114  (-*--)
                         -------+---------+---------+---------+--
                            14000     21000     28000     35000

Pooled StDev = 7028
```

One-way ANOVA: h_gap_mid versus c_jump

```
Source   DF           SS         MS     F      P
c_jump    2       316045     158022  0.00  0.999
Error   226  28641572844  126732623
Total   228  28641888889

S = 11258   R-Sq = 0.00%   R-Sq(adj) = 0.00%


                           Individual 95% CIs For Mean Based on
                           Pooled StDev
Level   N   Mean  StDev  -------+---------+---------+---------+--
4317   77  21144  11375   (----------------*----------------)
5756   76  21121  11284   (----------------*----------------)
7195   76  21057  11111  (----------------*----------------)
                         -------+---------+---------+---------+--
                            19500     21000     22500     24000

Pooled StDev = 11258
```

One-way ANOVA: h_gap_mid versus kf_mult

```
Source    DF           SS          MS      F      P
kf_mult    2   7246482340  3623241170  38.27  0.000
Error    226  21395406549    94669940
Total    228  28641888889

S = 9730   R-Sq = 25.30%   R-Sq(adj) = 24.64%


                           Individual 95% CIs For Mean Based on
                           Pooled StDev
Level   N   Mean  StDev  ----+---------+---------+---------+-----
0.75   72  15399   6226  (----*---)
1.00   77  18695   8168        (---*----)
1.25   80  28567  13107                           (---*---)
                         ----+---------+---------+---------+-----
                         15000     20000     25000     30000

Pooled StDev = 9730
```

One-way ANOVA: h_gap_mid versus kg_mult

```
Source     DF           SS         MS     F      P
kg_mult     2    516390034  258195017  2.07  0.128
Error     226  28125498855  124449110
Total     228  28641888889

S = 11156   R-Sq = 1.80%   R-Sq(adj) = 0.93%


                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level   N   Mean  StDev   ---+---------+---------+---------+------
0.9    74  19261  10006   (---------*---------)
1.0    77  21020  11081          (---------*---------)
1.1    78  22946  12212                  (---------*---------)
                          ---+---------+---------+---------+------
                         17500     20000     22500     25000

Pooled StDev = 11156
```

One-way ANOVA: h_gap_mid versus c_contact

```
Source       DF           SS         MS     F      P
c_contact     2    906164244  453082122  3.69  0.026
Error       226  27735724645  122724445
Total       228  28641888889

S = 11078   R-Sq = 3.16%   R-Sq(adj) = 2.31%


                         Individual 95% CIs For Mean Based on Pooled StDev
Level   N   Mean  StDev    --+---------+---------+---------+-------
 5     81  19477  11143    (---------*---------)
10     81  20210  11197       (---------*---------)
20     67  24163  10852                      (----------*---------)
                           --+---------+---------+---------+-------
                         17500     20000     22500     25000

Pooled StDev = 11078
```

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